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Recovery behaviour resulting from thermal annealing in n-MOSFETs irradiated by 20 MeV protons

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Abstract
The radiation damage of 20 MeV proton irradiated n-MOSFETs fabricated in a BiCMOS process is studied. From the input characteristics of the drain current, the activation energy of the voltage shift based on trapped-oxide charge (ΔV_{Not}) and SiO_2/Si interface traps (ΔV_{Nit}) for a total ionizing dose of 35 Mrad(Si) is calculated to be 0.40 and 0.26 eV, respectively. Also, the activation energy for the annealing of the density of radiation-induced interface traps (N_{it}) estimated from the base current of the bipolar mode operation corresponds to 0.27 eV. From the activation energy of the ohmic drain–source current recovery of 0.40 eV it can be concluded that the trapped-oxide charge is mainly responsible for the degradation of the transistor performance.

1. Introduction

An important segment of the aerospace/military integrated circuit market needs radiation-hard devices with an increasing importance for space applications. MOSFETs are basic building blocks of ULSI circuits. Therefore, to study the degradation of the device performance and its recovery by thermal annealing after irradiation in MOSFETs is useful, both from the fundamental and application viewpoint. It is well known that the oxide trap (N_{ot}) and SiO_2/Si interface trap density (N_{it}) are dominant for the degradation of the current–voltage (I–V) characteristics in irradiated MOSFETs. More in particular, the threshold voltage of the drain current in the ohmic regime is directly influenced by these factors. The effects of trapped-oxide charge and SiO_2/Si interface traps on the threshold voltage shift have been discussed extensively, but most studies rely on a simple charge-separation procedure introduced by McWhorter and Winokur [1]. Maybe less popular is the extraction of N_{it} from the base current measured by the bipolar operation or gated-diode mode of MOSFETs [2–5]. In principle, both methods should yield similar results for the radiation-induced N_{it}, for a uniform distribution.

In this paper, the radiation damage of 20 MeV proton irradiated n-MOSFETs fabricated in a BiCMOS process was studied using the degradation and recovery behaviour of the threshold voltage, which can be separated into a contribution due to trapped-oxide charge and SiO_2/Si interface traps [1], and of the base current from source to substrate of a MOSFET in the bipolar operation mode. In order to identify the main degradation mechanism of the device performance, the activation energy derived from isochronal thermal annealing was investigated. Based on the experimental results, it is demonstrated that the trapped-oxide charge is mainly

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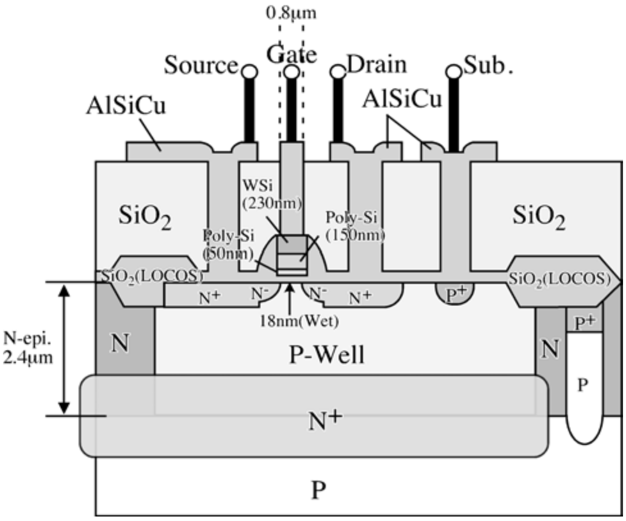

Figure 1. Schematic structure of the used n-MOSFETs.

responsible for the decrease of the drain current in the linear operation regime.

2. Experimental details

The n-MOSFETs fabricated by a typical BiCMOS process have a lightly doped drain structure and are formed in the p-well region, processed in an n-type epitaxial wafer. The resistivity of the n-type epitaxial layer was 1.2 Ω cm and its thickness was 2.4 μm. An 18 nm thick wet gate oxide was grown at 820 °C by a pyrogenic technique, whereby H_2 and O_2 react to form water vapour. The gate length and width are 0.8 μm and 20 μm. A standard local oxidation of silicon process was used for isolation. Source, gate, drain and substrate metallization with 500 nm thickness was performed by sputtering of AlSiCu. A schematic structure of the studied n-MOSFETs is shown in figure 1.

The samples were irradiated by a 20 MeV proton beam at room temperature using the AVF cyclotron in TIARA at Takasaki JAERI. The proton total ionizing dose was varied between 350 krad(Si) and 35 Mrad(Si) and corresponds to a fluence of 1×10^{12} and 1×10^{14} cm^{-2}, respectively. Perpendicular irradiation was performed without sample bias. The device performance, i.e., drain-to-source current (I_{DS}) as a function of gate-to-source bias V_{GS} (input characteristics) was measured at room temperature before and after irradiation. The drain-to-source bias V_{DS} is fixed at 0.1 V.

To estimate the interface trap density, the base current (I_B) in the bipolar operation mode was measured before and after irradiation. The measurement method of I_B and the principle of the bipolar operation mode were defined in [2–5]. I_B of the lateral bipolar transistor (n-MOSFET in bipolar mode) can be at least partially attributed to the surface recombination through fast interface states. I_B as a function of V_{GS} at a base (substrate) to emitter (source) voltage $V_{BE} = 0.4$ V was measured before and after irradiation. The height of the I_B peak, obvious in figure 2(*b*) is denoted by ΔI_B and corresponds to the surface recombination leakage current, with density per unit area $J_s = \Delta I_B/A$ (A the gate area). J_s can easily be expressed in terms of N_{it} based on the conventional Shockley–Read–Hall theory, whereby N_{it} can be expressed by [2–5]

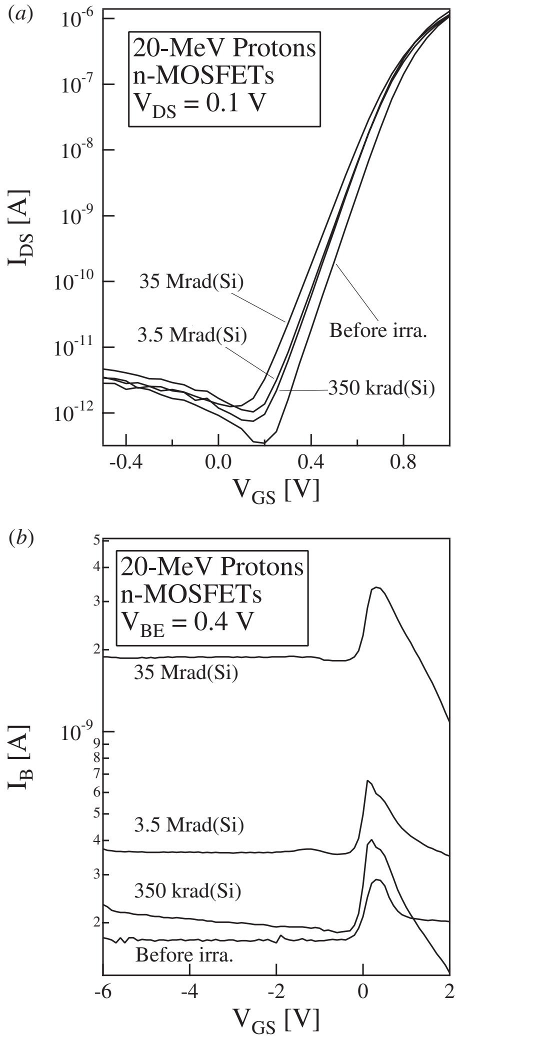

Figure 2. Typical I_{DS}–V_{GS} (*a*) and I_B–V_{GS} (*b*) characteristics before and after a 20 MeV proton irradiation.

$$N_{it} = J_s \left[\frac{q \sigma v_{th} n_i}{2} \left(e^{\frac{qV_{BE}}{2k_B T}} - 1 \right) \right]^{-1} \tag{1}$$

where σ is the carrier capture cross section (estimated 10^{-15} cm^2) and v_{th} the thermal velocity (10^7 cm s^{-1}), n_i the intrinsic electron density (1.45×10^{10} cm^{-3}), k_B the Boltzmann constant and T the temperature; q is the elementary charge. Here, dimension of the N_{it} is cm^{-2}.

To investigate the recovery behaviour of the degraded transistors and to calculate the activation energy of the recovery process, isochronal thermal annealing for 15 min was carried out at temperatures between 100 and 300 °C under nitrogen gas ambient, without bias.

3. Results and discussion

Typical I_{DS}–V_{GS} and I_B–V_{GS} characteristics before and after a 20 MeV proton irradiation for different doses are shown in figures 2(*a*) and (*b*), respectively. From the I_{DS}–V_{GS} characteristics, it is derived that I_{DS} increases after irradiation,

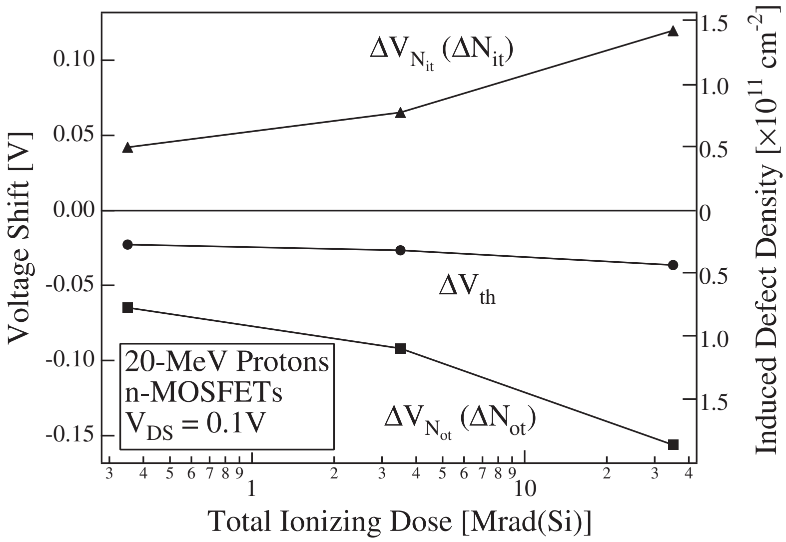

Figure 3. Separation of the threshold voltage shift (ΔV_{th}) in ΔV_{Not} and ΔV_{Nit} estimated from I_{DS}–V_{GS} characteristics at $V_{DS} = 0.1$ V after 20 MeV proton irradiations for different fluences.

which is mainly due to the negative shift of the threshold voltage. This negative shift is thought to originate from the change in balance between the positive trapped-oxide charge and the negative interface trap charge. Note also the slight reduction in the subthreshold slope, indicating the creation of interface traps due to the proton irradiation [1].

From the I_B–V_{GS} characteristics, it is noted that both I_B and ΔI_B increase after irradiation. According to equation (1), this increase is related to an increase of the interface trap density by irradiation, provided that the capture cross section σ remains constant.

Using the I_{DS}–V_{GS} subthreshold characteristics [1] at V_{DS} which is 0.1 V, ΔV_{th} was separated into ΔV_{Not} and ΔV_{Nit} as shown in figure 3. The created densities of oxide (ΔN_{ot}) and interface traps (ΔN_{it}) by the proton irradiation are easily determined from ΔV_{Not} and ΔV_{Nit} as

$$\Delta N = \Delta V_{th} C_{ox}/q \tag{2}$$

where C_{ox} is the capacitance density of the gate oxide. The values of ΔN_{ot} and ΔN_{it} are indicated on the right axis of figure 3. The radiation-induced total threshold voltage shift is negative because ΔN_{ot} is larger than ΔN_{it}. On the other hand, ΔV_{th} varies less with the fluence than its components. This is because the generation rate of ΔN_{ot} and ΔN_{it} is nearly the same.

Next, the recovery behaviour by isochronal annealing was investigated. A typical annealing result of the I_{DS}–V_{GS} characteristics of a 35 Mrad(Si) proton-irradiated n-MOSFET is shown in figure 4. The drain current recovers by annealing, e.g., to about 85% of the pre-rad value after 15 min at 300 °C. From figure 4, the voltage shifts and induced defect densities were calculated as shown in figure 5. ΔN_{ot} and ΔN_{it} decrease with increasing annealing temperature. However, ΔN_{ot} and ΔN_{it} are not completely annealed after the 300 °C 15 min annealing. Therefore, a further annealing step is required for a complete recovery of the device performance.

The activation energies of the recovery process by the annealing have been estimated as follows. The unannealed fraction (f_V) and annealing rate ($1/\tau_V$) of the oxide and interface trap density for 35 Mrad(Si) proton-irradiated n-MOSFETs are shown in figures 6(*a*) and (*b*), respectively. The f_V is defined as [6]

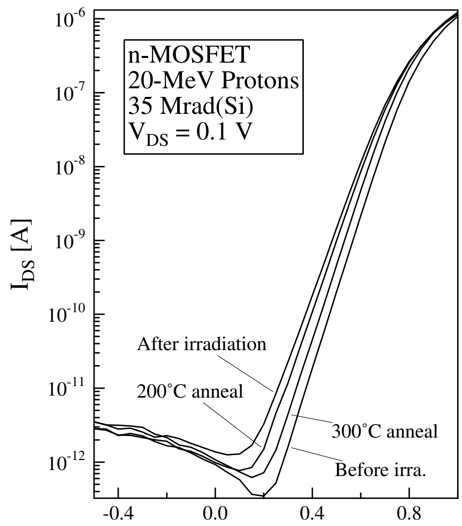

Figure 4. Impact of 15 min isochronal annealing on the drain current in linear operation of a 0.8 μm × 0.8 μm n-MOSFET.

$$f_V = \frac{\Delta V_{AA}}{\Delta V_A} \tag{3}$$

where ΔV_{AA} is the difference of the threshold voltage shifts observed before irradiation and after annealing, and ΔV_A the difference of the voltage shifts before and after irradiation. From figure 6(*a*), f_V is seen to rapidly decrease above about 200 °C. This means that the MOSFET performance recovers progressively in this temperature region.

In addition to that, the recovery rate of the interface traps is faster than the one of the oxide-trapped charge.

If the recovery process behaves according to a first-order reaction [7], the relationship between f_V and the annealing

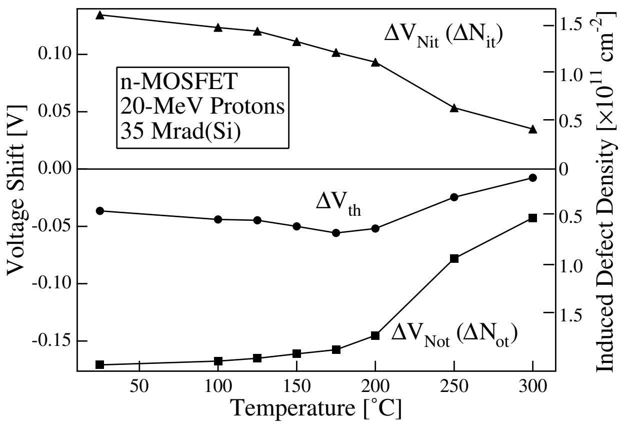

Figure 5. The voltage shifts against the annealing temperature.

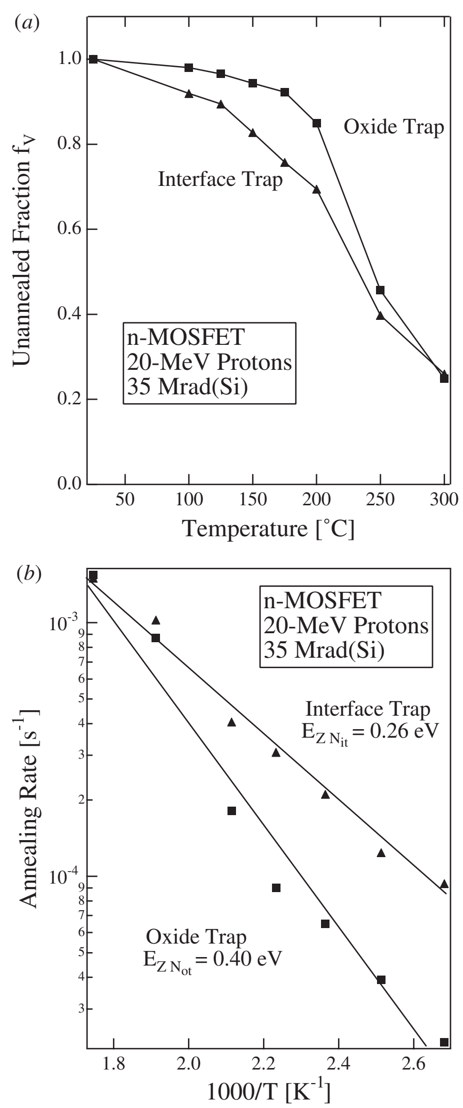

Figure 6. Unannealed fraction (f_V) (a) and annealing rate $(1/\tau_V)$ of trapped-oxide charge and interface trap density for 35 Mrad(Si) proton-irradiated n-MOSFETs.

rate $(1/\tau_V)$ of the voltage shifts obeys

$$f_V = \exp\left(-\frac{t}{\tau_V}\right) \tag{4}$$

where t is the annealing time. For a thermally activated process, $1/\tau_V$ is given by the following equation [8, 9]:

$$\frac{1}{\tau_V} = \nu_0 \exp\left(-\frac{E_Z}{k_B T}\right) \tag{5}$$

where ν_0 is the frequency factor and E_Z the activation energy of the recovery process. As shown in figure 6(b) the Arrhenius plots of the annealing rate are linear for both voltage shifts. The E_Z of trapped-oxide charge and interface trap density are 0.40 and 0.26 eV, respectively. The activation energy for the other proton fluences studied is nearly the same. This result means that the same type of defects appear after irradiation for the investigated proton fluence range.

The values found in the literature for the activation energy of the MOSFET performance recovery upon thermal annealing cover a broad range [6, 10, 11]. For example, Stahlbush *et al* irradiated 1 or 10 Mrad(SiO_2) x-rays with a bias of 1 MV cm^{-1} to the gate oxide and estimated an activation energy of about 0.9 eV for ΔN_{ot} [11]. On the other hand, Lelis *et al* irradiated 20 krad(SiO_2) x-rays to the samples with a bias of 1.25 MV cm^{-1}, and an E_Z of 0.27 eV for ΔN_{ot} was derived [10]. The difference of the experimental activation energies can be explained by the dependence of E_Z on the applied gate bias during the annealing.

It is well established nowadays that one of the main hole trapping centres responsible for irradiation-induced positive charge is the E′-centre [12]. Electron spin resonance (ESR) studies have revealed that the E′-centre is a defect resulting from an oxygen vacancy in SiO_2. A direct correlation has been established between the annealing of the oxide-trapped charge and of the E′-centres observed in ESR [12]. This annealing typically occurs in the temperature range between 100 and 300 °C, as in figure 6(a).

The key SiO_2/Si interface defect is called Pb-centre and corresponds to a silicon dangling bond at the interface, back-bonded by three other silicon atoms [12]. There is good agreement between the density of interface traps and of the Pb-centres. Passivation of these dangling bonds (DBs) occurs through binding with hydrogen. On the other hand, interaction of a passivated DB with a proton, released from the oxide or polysilicon gate by the irradiation creates new DBs and, hence, an increase of N_{it}. The activation energy of 0.26 eV observed in this work for the annealing of the interface traps is in good agreement with the activation energy of ~0.3 eV believed to correspond with the diffusion of hydrogen in silicon [13, 14]. The annealing of the radiation-induced interface traps is thus governed by the transport of hydrogen towards the interface, where a passivation of the DBs occurs.

The dependence of the interface trap density on the annealing temperature, estimated from I_B–V_{GS} characteristics using equation (1), is shown in figure 7(a). N_{it} decreases with increasing annealing temperature. Comparing the results of figures 5 and 7, a roughly four times higher value of N_{it} is found from the gated-diode technique. This difference could stem from the assumed value of the capture cross section [5], whereby the charge-separation technique does not require any knowledge about σ.

The Arrhenius plot of annealing rate is shown in figure 7(b). $1/\tau_{Nit}$ is also calculated from equations (3) to (5). From figure 7(b), the activation energy of removal of the

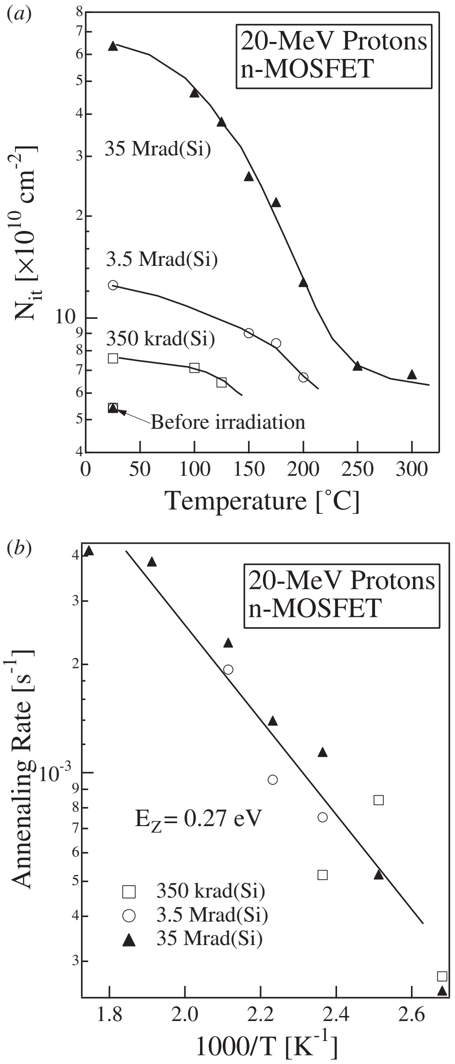

Figure 7. Temperature dependence of N_{it} (*a*) and Arrhenius plot of the annealing rate ($1/\tau_{Nit}$) (*b*).

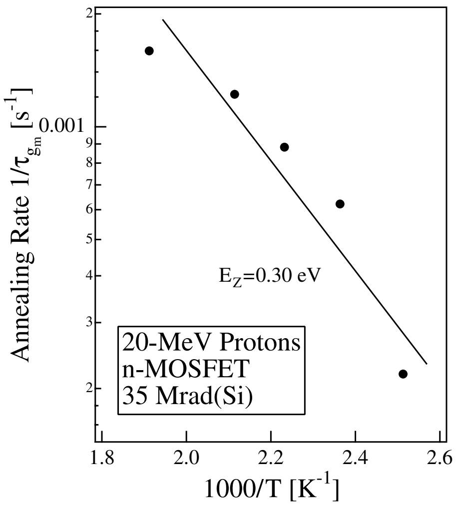

Figure 8. Recovery behaviour of the transconductance (g_m).

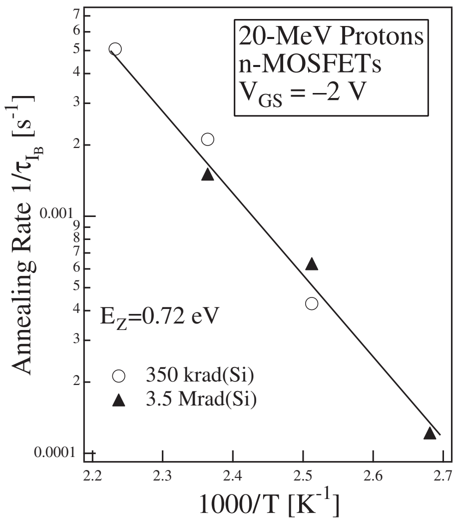

Figure 9. The annealing rate of I_B at $V_{GS} = -2$ V for 20 MeV proton irradiation to an equivalent dose of 350 krad(Si) and 3.5 Mrad(Si).

interface trap density is 0.27 eV and this value is again independent of the 20 MeV proton fluence. Therefore, the recovery mode is not dependent on the degree of degradation, for the studied fluence range.

In our previous paper, the activation energy of I_{DS} recovery by isochronal annealing was found to be 0.40 eV [15]. This value agrees quite well with the activation energy of recovery of the trapped-oxide charge. This means that the degradation and recovery of I_{DS} are mainly influenced by the trapped-oxide charge. However, one should also account for the impact of the mobility degradation, since the drain current in strong inversion can be written as $I_{DS} = g_m(V_{GS}-V_{th})$. Hereby g_m is the device transconductance. We also calculated the activation energy of the annealing behaviour of the g_m, which is represented in figure 8. A value of 0.27 eV is found, which agrees with the energy of ΔN_{it}. This implies that the mobility is mainly affected by the annealing of the interface traps, through coulombic scattering.

Finally, bulk displacement damage in the silicon substrate by proton irradiation is investigated. The base current I_B below $V_{GS} = 0$ V is related to the drain-bulk diode leakage current. The annealing rate of the I_B at $V_{GS} = -2$ V is shown in figure 9. From the slope of the annealing rate, an activation energy of 0.72 eV could be estimated. The value is higher than the activation energies of ΔN_{ot} and ΔN_{it}, and may correspond to the combined annealing of the *V*–*V* or the *C*-related centre [16].

4. Conclusions

The influence of trapped-oxide charge and SiO_2/Si interface traps on the degradation and recovery behaviour of device performance of n-MOSFETs irradiated by 20 MeV protons was studied. The activation energy of ΔN_{ot} was calculated to be 0.40 eV and this value agrees with that derived from the isochronal annealing of the linear drain current in strong inversion. From this result it is concluded that the degradation and recovery of the device performance are mainly caused by trapped-oxide charge.

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