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Frédéric Saigné, Laurent Dusseau, Jean Fesquet, Jean Gasiot, Robert Ecoffet, et al.. Prediction of the one-year thermal annealing of irradiated commercial devices based on experimental isochronal curves. IEEE Transactions on Nuclear Science, 2000, 47 (6), pp.2244-2248. 10.1109/23.903760 . hal-01801668

HAL Id: hal-01801668

<https://hal.science/hal-01801668v1>

Submitted on 17 Dec 2024

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Prediction of the One-Year Thermal Annealing of Irradiated Commercial Devices Based on Experimental Isochronal Curves

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Abstract—In a previous paper, a method was proposed to predict the thermal annealing of irradiated devices from a single experimental isochronal curve. In this paper, the method is applied to four different power MOSFETs. It is shown that for one of the devices the method can not be applied, whereas for the other three devices, the one-year isothermal behavior is predicted with good accuracy. The predicted and experimental isothermal curves are compared for temperatures of 60°C and 90°C. The range of validity of this method is discussed.

I. INTRODUCTION

IONIZING radiation exposure of MOS (metal oxide semiconductor) devices results in a buildup of trapped charge in the oxide and an increase in the interface trap density at the Si/SiO₂ interface. Both processes lead to the degradation of device electrical parameters. In a radiation environment, radiation-induced trapping processes and annealing [1] can be considered to be independent, simultaneous, and competitive. The annealing rate depends on the temperature [2] and the bias [3]. Due to the different time constants of these processes, the measured device characteristics shift differently as a function of time, depending on the dose rate at which the total dose is accumulated. A prediction method to be applied to devices in a radiation environment was presented in a previous paper [4], considering the thermally activated annealing process only. This method, based on a single experimental isochronal annealing curve, allows extraction of the oxide trapped charge characteristics leading to the prediction of the isothermal annealing of irradiated devices.

In that paper, this method is used for the first time to predict the thermal behavior of four different commercial devices over a one-year time period.

For one of the devices, it is shown that the method cannot be used as proposed. Nevertheless, the method made it possible to identify that the device was likely to fail in flight. For the other devices, the predicted isothermal curves obtained on commercial power MOSFETs are presented and compared with

the experimental isothermal curves measured at two different temperatures (60°C and 90°C). After one year, the maximum difference between the predicted long-term thermal behavior and the experimental isothermal results is about 12%. Although the model does not take into account the effect of bias, biased isothermal annealing was also performed to show the influence of the bias on the annealing.

After a brief review of the experimental procedure we will report the experimental results. The range of application of the method is discussed in Section IV.

II. THE EXPERIMENTAL PROCEDURE

Experiments were performed on four types of commercial power MOSFETs (IRF230, IRF450, BUK456 and P50N06). In order to verify the reproducibility of the experimental results, four samples of each device type were characterized. The gate-oxide thickness of the devices is on the order of 100 nm. Irradiations were performed at room temperature with a ⁶⁰Co source to a 23 krd(Si) total dose at 0.12 rd(Si)/s. A 9 V gate-substrate bias was applied during the irradiation. The devices were then characterized using the isochronal annealing method [4]. This technique consists of emptying sequentially a fraction of the traps by brief annealing periods at increasing temperature. After each annealing step, the electrical characteristics are measured at room temperature. This annealing was performed using a 20°C temperature step function and a 360 s dwell time. As the goal of the experiments is to study the thermal annealing of the net oxide-trapped charge without the complicating effects of other mechanisms like tunneling, no bias is applied during isochronal and isothermal annealing to avoid the influence of the electric field. For each device, the degradation and recovery were monitored by measuring the threshold-voltage shift. This parameter was normalized to unity and the unannealed fraction of this quantity

$$N = \frac{V_{th} - V_{th}(\text{before irradiation})}{V_{th}(\text{after irradiation}) - V_{th}(\text{before irradiation})} \quad (1)$$

was used to quantify the annealing process [5]. Since only the charge trapped in the bulk of the oxide is considered in this method, devices in which the oxide trapped charge is dominant were chosen. This is usually true in power MOSFETs because of their relatively thick gate oxide. In order to estimate

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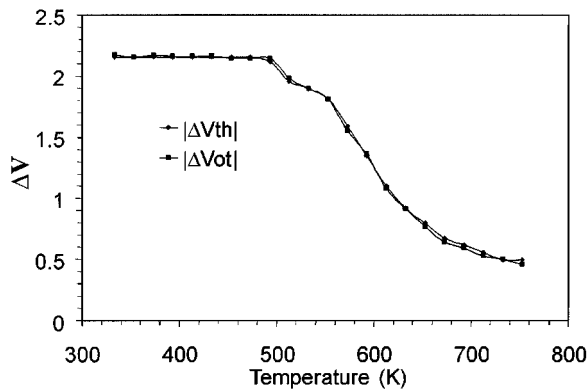


Fig. 1. Experimental isochronal annealing curve of an IRF230 irradiated to a total dose of 23 krd(Si). Dose rate was 0.12 rd(Si)/s. The device is not biased.

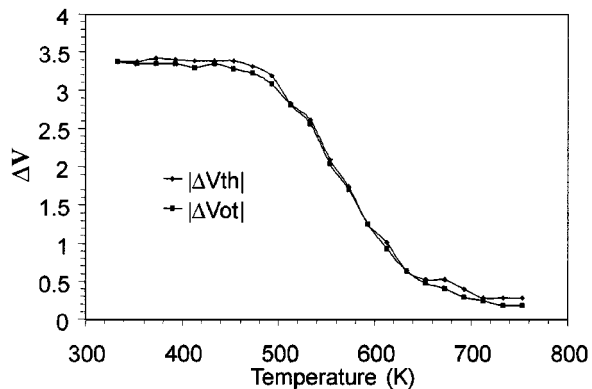


Fig. 3. Experimental isochronal annealing curve of an IRF450 irradiated to a total dose of 23 krd(Si). Dose rate was 0.12 rd(Si)/s. The device is not biased.

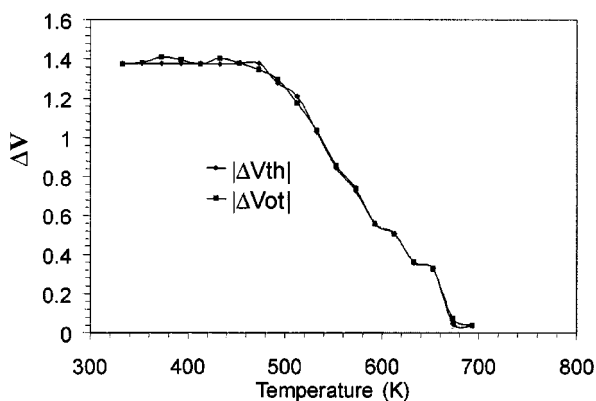


Fig. 2. Experimental isochronal annealing curve of a BUK456 irradiated to a total dose of 23 krd(Si). Dose rate was 0.12 rd(Si)/s. The device is not biased.

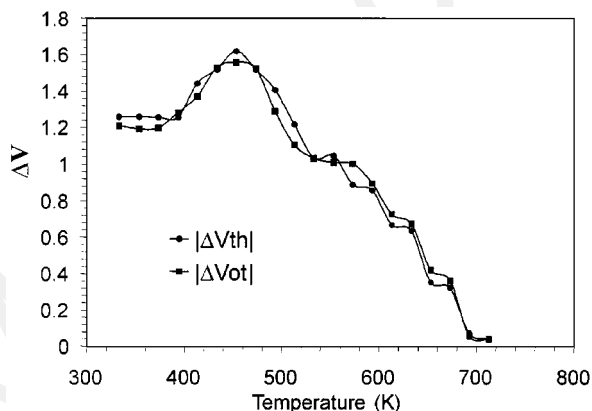


Fig. 4. Experimental isochronal annealing curve of a P50N06 irradiated to a total dose of 23 krd(Si). Dose rate was 0.12 rd(Si)/s. The device is not biased.

the contributions of oxide trapped charge and interface traps, the subthreshold charge-separation technique [6] was used. This paper compares the predicted long-term thermal behavior with experimental data recorded during isothermal annealing performed at 90°C and 60°C over a one-year time period. The experimental isothermal temperatures were chosen to validate the applicability of the method to real systems. The temperatures are sufficiently high that significant annealing takes place during the one-year duration of the experiments, but are still close to temperatures encountered during realistic missions.

The effect of the bias during annealing is not taken into account by the model, but in order to examine the effect of the annealing bias, biased isothermal experiments at 60°C and 90°C for one year were also performed. For the biased experiments, a 9 V gate-substrate voltage was applied during the annealing of the devices. This bias is the same as that applied during the irradiations.

III. THE EXPERIMENTAL RESULTS

The experimental isochronal curves are shown in Figs. 1–4. In these curves, the absolute values of the net threshold-voltage shift ($|\Delta V_{th}|$) and the contribution due to trapped-oxide charge ($|\Delta V_{ot}|$) are plotted as functions of temperature, for the IRF230, BUK456, IRF450, and P50N06, respectively. The good correlation between $|\Delta V_{th}|$ and $|\Delta V_{ot}|$ on these curves confirms the

assumption of a negligible contribution of interface states on the results.

The isochronal method is based on the extraction of both the so-called characteristic temperature of each trap level, T^* , and the proportion of traps occupied at this temperature. Each T^* corresponds to a transition temperature, or inflection point, on the annealing curve associated with a particular activation energy level [4]. From these data, the isothermal annealing curves of the considered devices can be predicted for different temperatures. However, to allow accurate prediction of the isothermal annealing, it is evident that the experimental isochronal curve has to be easily interpretable.

In Figs. 1–3, using the method summarized in the appendix, T^* for each device can be extracted, as well as the proportion of traps occupied at these temperatures. This is not possible in the P50N06 case (Fig. 4). Since the degradation increases during the annealing of this device, a meaningful value of T^* cannot be extracted. This curve represents an example of a case in which the method cannot be applied. This increase of the degradation during the annealing time could be attributed to the detrapping of compensating electrons [7]. Although this behavior makes it impossible to apply the method described in this paper to this type of device, the isochronal annealing still makes it possible to identify this enhanced degradation and screen the device.

The goal of this paper is to show that, when the characteristics of the oxide trapped charge can be obtained from isochronal

TABLE I

VALUES OF T^* EXTRACTED FROM THE EXPERIMENTAL ISOCHRONAL CURVES FOR ALL THE DEVICES. THE CALCULATED ACTIVATION ENERGIES AND TIME CONSTANTS (AT 60°C AND 90°C) FOR EACH T^* ARE ALSO REPORTED FOR A $1 \times 10^7 \text{ s}^{-1}$ EFFECTIVE FREQUENCY FACTOR VALUE

Device	T^* (K)	Activation Energy (eV)	Time constant (s) At 60°C	Time constant (s) At 90°C
BUK456	525	1	1.3×10^8	7.3×10^6
	595	1.14	1.7×10^{10}	6.3×10^8
	630	1.22	2.7×10^{11}	8.1×10^9
	680	1.31	6.2×10^{12}	1.4×10^{11}
IRF230	520	0.99	9.1×10^7	5.3×10^6
	590	1.13	1.2×10^{10}	4.6×10^8
	640	1.24	5.4×10^{11}	1.5×10^{10}
	690	1.34	1.77×10^{13}	3.7×10^{11}
IRF450	780	1.52	9.3×10^{15}	1.2×10^{14}
	530	1.02	2.6×10^8	1.4×10^7
	600	1.15	2.4×10^{10}	8.7×10^8
	635	1.23	3.9×10^{11}	1.1×10^{10}
	690	1.34	1.7×10^{13}	3.7×10^{11}
	750	1.46	1.1×10^{15}	1.7×10^{13}

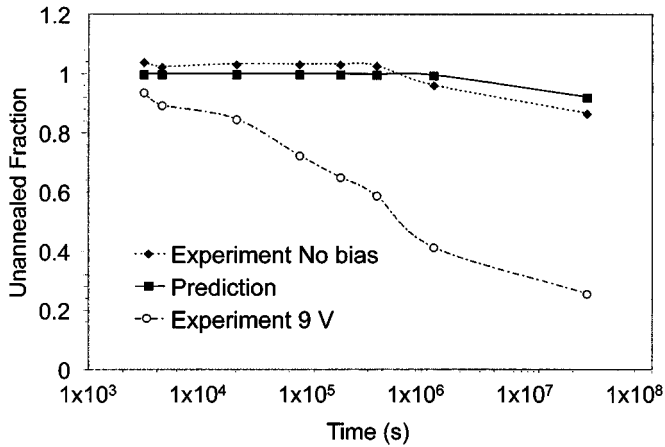


Fig. 5. Experimental and predicted isothermal annealing curve at 60°C of an IRF230 irradiated to a total dose of 23 krd(Si). Dose rate was 0.12 rd(Si)/s.

curves, the thermal behavior of irradiated devices can be predicted over a long period of time at any temperature. Thus, only the easily interpretable curves will be used to predict the isothermal annealing (Figs. 1–3).

Note that in a previous paper [8], it was shown that it is not necessary to reach a temperature as high as 700K (427°C) during the isochronal annealing to obtain the relevant characteristics describing the thermal annealing of the oxide trapped charge. For a one-year experiment at 90°C, the temperature needed as that all the range of possible detrapping processes is covered is about 270°C (543K). The higher-temperature data are not necessary for the prediction.

Once the oxide trapped charge characteristics are extracted from the isochronal curves (Table I), the isothermal annealing can be predicted using the method presented in [4] and [8]. In Figs. 5–10, the experimental and predicted unannealed fraction, as defined in (1), are plotted versus annealing time for both 60°C and 90°C isothermal temperatures, as well as the

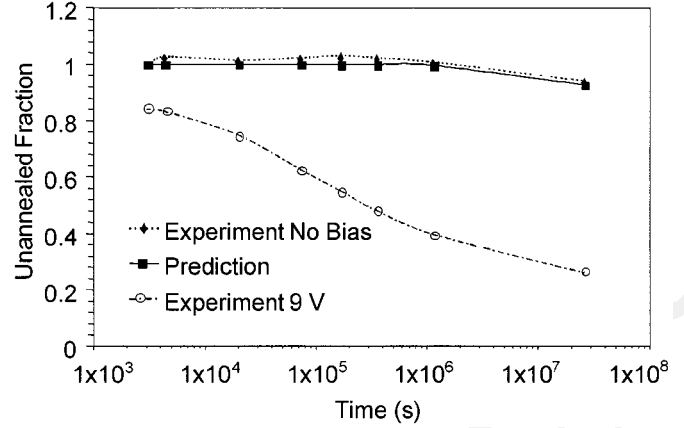


Fig. 6. Experimental and predicted isothermal annealing curve at 60°C of a BUK456 irradiated to a total dose of 23 krd(Si). Dose rate was 0.12 rd(Si)/s.

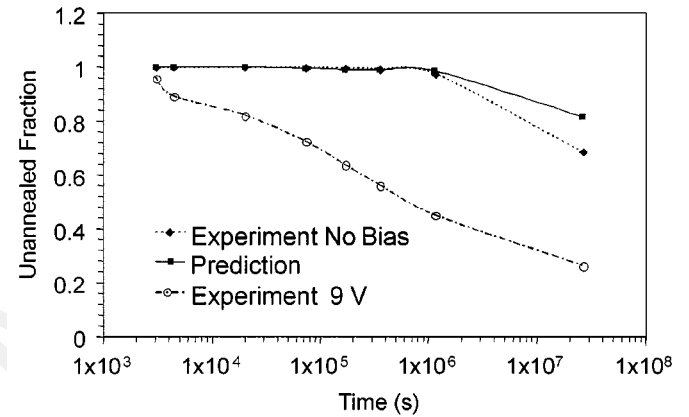


Fig. 7. Experimental and predicted isothermal annealing curve at 60°C of an IRF450 irradiated to a total dose of 23 krd(Si). Dose rate was 0.12 rd(Si)/s.

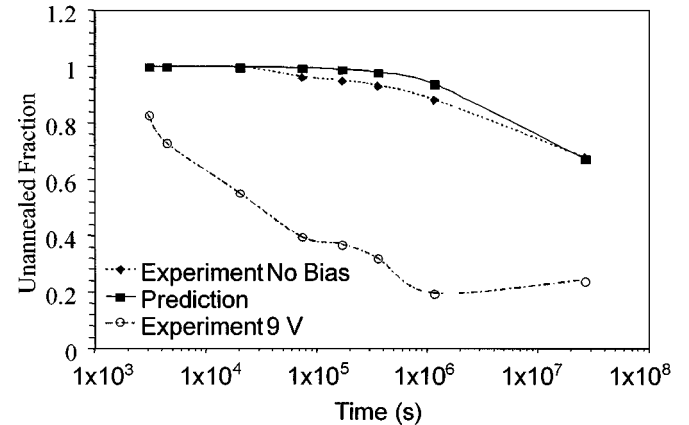


Fig. 8. Experimental and predicted isothermal annealing curve at 90°C of an IRF230 irradiated to a total dose of 23 krd(Si). Dose rate was 0.12 rd(Si)/s.

isothermal curves when the devices are biased. The maximum difference between the prediction and the unbiased experiment is about 10% (IRF450) for the 60°C isothermal annealing and 12% (IRF450) for the 90°C isothermal annealing. Regarding the biased experiments, the recovery of the devices is larger than in the unbiased case, as expected [9]. This point is discussed in the next section, along with the range of application of the method.

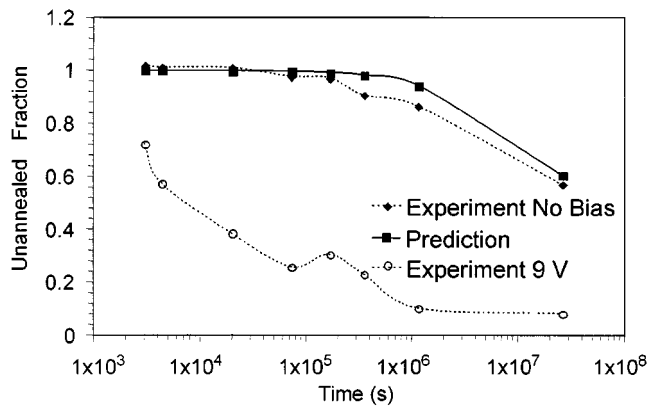


Fig. 9. Experimental and predicted isothermal annealing curve at 90°C of a BUK456 irradiated to a total dose of 23 krd(Si). Dose rate was 0.12 rd(Si)/s.

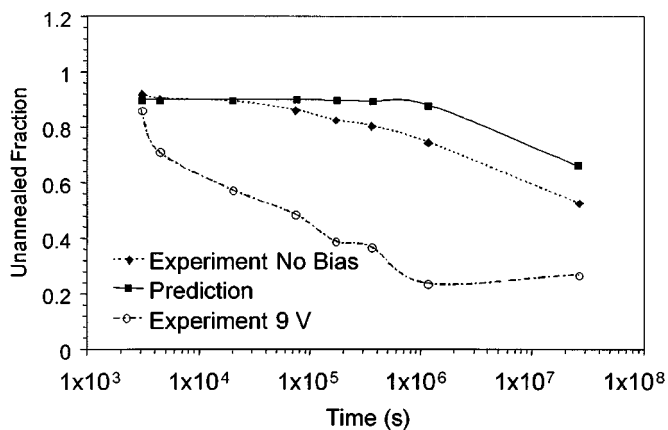


Fig. 10. Experimental and predicted isothermal annealing curve at 90°C of an IRF450 irradiated to a total dose of 23 krd(Si). Dose rate was 0.12 rd(Si)/s.

IV. DISCUSSION

From a hardness-assurance point of view, it is important to estimate as accurately as possible the degradation of an irradiated device during the mission. The degradation and the recovery of the device have to be taken into account without overestimating the recovery. Due to the sensitivity of commercial devices and the current trend to reduce the error margins, it is critical for the characterization test to predict as closely as possible the response of the devices for the actual mission conditions.

The present paper has established experimentally that the isochronal method allows prediction of the thermal behavior of appropriate unbiased devices at different temperatures. The experiments were conducted over a one-year time period. This method of taking into account the parameters of the device and the mission (duration, temperature) leads to a better estimation of the thermal behavior of irradiated devices than a fixed annealing process. Using the isochronal method the maximum difference between the experiment and the prediction is small (12%) for all of the experimental conditions. From a hardness-assurance point of view, the prediction has to be as close as possible to the experimental result without overestimating the recovery of the device, which is not the case for the BUK456 power MOSFET (Fig. 6). However, it is important to point out that no electric field is applied during the

annealing, unlike typical mission conditions where irradiation and annealing take place simultaneously. It has been shown that applying a bias during annealing leads to a much greater recovery of the irradiated devices [9]. Even if the devices are biased off, they will recover by the RICN (radiation induced charge neutralization) process [10] which allows the recovery of irradiated devices by alternating (on then off) biases. So the slight difference, observed for the BUK456 in Fig. 6 between the prediction and the experimental result with no bias will never result in a nonconservative prediction of the threshold-voltage shift under real conditions.

Thus, the isochronal method provides good accuracy in predicting the thermal behavior of irradiated devices, but still provides a conservative estimate compared to the biased behavior. This means that the prediction is close to the real annealing behavior of devices that are unbiased during annealing, but still overestimates the degradation of devices that are biased during both irradiation and annealing. This work should be extended to take into account both the influence of the electric field and the interface traps. The electric field will play a role in the tunnel effect and also in the thermal annealing itself. As has been shown experimentally [11], the electric field can change the parameters of the annealing process drastically.

V. CONCLUSION

Experiments were performed for four different types of power MOSFETs to demonstrate the validity of a long-term thermal-behavior prediction method. For one device type, the extraction of the oxide-trap characteristics was not possible. In the other three cases, isothermal annealing of irradiated devices was performed at 60°C and 90°C for a one-year time period in order to compare the prediction and the experimental data. In these three cases, the isochronal experiments, performed within 5 hours, predicted the one-year thermal behavior with good accuracy, demonstrating the utility of the method within the limits of its range of validity. However, in order to be useful in more general applications, this method should be extended to take into account the effects of both electric field and interface traps.

APPENDIX

The method is based on the following fundamental assumptions: 1) the radiation damage (i.e., trapping of oxide charge), and the thermal annealing (i.e., detrapping of oxide charge), causing time-dependent effects are assumed to occur independently and are competitive; 2) the trapping rate is assumed to be proportional to the dose rate; and 3) the thermal detrapping probability is assumed to follow an Arrhenius law.

The first step of the method is the experimental determination of the trap characteristics (activation energy ϕ_0 and equivalent charge density Y_0) using an isochronal annealing curve. Isochronal experiments are based on the measurement of an electrical parameter Y (voltage or current) related to the annealing of the trapped charge as a function of temperature (Fig. 11). In the case of a single trap, the inflection point of the $Y(T)$ curve [or maximum value of $dY(T)/dT$] is called the characteristic temperature T^* . For this temperature value,

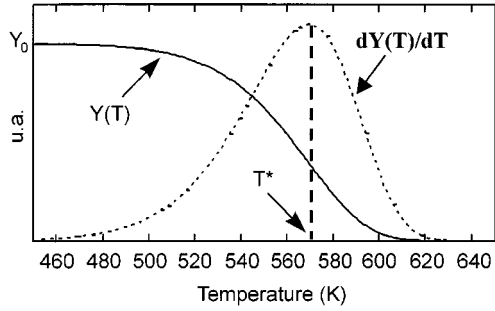


Fig. 11. Experimental determination of the trap characteristics from isochronal annealing.

the effective frequency factor F , the heating rate c , and ϕ_0 the activation energy associated with T^* are related by (A1).

$$\frac{\Phi_0}{kT^*} = \ln \left(\frac{FkT^{*2}}{c\Phi_0} \right). \quad (\text{A1})$$

The heating rate is determined experimentally. Then for a given effective frequency factor, (A1) makes it possible to calculate the activation energy associated with any experimental value of the characteristic temperature T^* . Note that Y_0 , corresponding to the initial trapped-charge density, can be determined by integrating the $dY(T)/dT$ curve as shown in Fig. 11.

The second step is the prediction of the isothermal annealing behavior from the experimentally-deduced trap characteristics. The detrapping probability is assumed to follow an Arrhenius law; hence the annealing of the trapped charge as a function of time at constant temperature can be represented by (A2):

$$Y(t) = Y_0 \exp(-\sigma t) \quad (\text{A2})$$

Here σ is defined as the probability per unit time for a charge to be released from its trap, through the Arrhenius relation:

$$\sigma = F \exp \left(-\frac{\Phi_0}{kT} \right) \quad (\text{A3})$$

where T is the annealing temperature in Kelvin. The time value associated with the probability σ is termed the time constant $\tau = 1/\sigma$. To predict the isothermal annealing behavior, σ must be determined. From the isochronal annealing curve, the characteristic temperature T^* , and the initial charge density Y_0 are measured. Substituting this value of T^* in (A1) leads to the characteristic activation energy ϕ_0 . Using ϕ_0 in (A3), for an isothermal temperature T , provides the σ value. The isothermal

annealing curve can then be predicted from (A2). This procedure presented for a single trap level can be extended to n levels by summing the contribution of each trap. Then, Equation (A2) and (A3) yield

$$Y(t) = \sum_{i=1}^n Y_{0i} \exp \left(-F \exp \left(-\frac{\Phi_{0i}}{kT} \right) t \right). \quad (\text{A4})$$

ACKNOWLEDGMENT

The authors wish to express their thanks to the Centre National d'Etudes Spatiales for its general support.

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