Compensation of Temperature Effects in Floating Gate Dosimeters

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Abstract

A study was conducted on the temperature effects of floating gate metal-oxide-semiconductor field-effect transistors (FGMOSFETs) used in floating gate dosimeters (FGDOS), and temperature compensation using the "zero temperature coefficient point" method was investigated. Through gamma-ray total dose irradiation tests and temperature stress tests, the threshold voltage variation of the devices before and after irradiation was observed, the changes in device transfer characteristic curves at different temperatures and the generation mechanism of the zero temperature coefficient point were investigated, the influence of dose on the accuracy of the "zero temperature coefficient point" method was discussed, and the effect of irradiation temperature on the total dose effect of the devices was studied. Experimental results revealed that dose has a minor impact on the device zero temperature coefficient point current I_{ZTC} and also a small effect on measurement accuracy; the "zero temperature coefficient point" method demonstrates significant suppression of temperature effects on radiation response, while irradiation temperature has a more pronounced influence on irradiation-induced threshold voltage shift.

Full Text

Discussion on Temperature Effect Compensation of Floating Gate Dosimeter

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Abstract

This study investigates the temperature effect of Floating Gate Metal Oxide Semiconductor Field Effect Transistors (FGMOSFET) employed in Floating Gate Dosimeters (FGDOS) and explores temperature compensation using the "zero temperature coefficient point" method. Through γ-ray total dose irradiation experiments and temperature stress tests, we observed threshold voltage changes in devices before and after irradiation, examined variations in transfer characteristic curves at different temperatures and the generation mechanism of the zero temperature coefficient point, investigated the impact of dose on the precision of the "zero temperature coefficient point" method, and studied the influence of irradiation temperature on the total dose effect. Experimental results demonstrate that dose has minimal effect on the zero temperature coefficient point current (I_{ZTC}) and negligible impact on measurement accuracy. The "zero temperature coefficient point" method significantly suppresses temperature sensitivity in radiation response, while irradiation temperature notably affects radiation-induced threshold voltage drift.

Keywords: floating gate dosimeter; total ionizing dose effect; temperature effect; zero temperature coefficient point

1. Experimental Methods

1.1 Irradiation Source and Device Information

Irradiation experiments were conducted at the Xinjiang Technical Institute of Physics & Chemistry, Chinese Academy of Sciences using a ^{60}Co γ-ray source. Two dose rates were employed: 5 rad(Si)/s and 13.17 rad(Si)/s, both with an error of less than $±$10%. Irradiation dose points were set at 0 krad(Si), 15 krad(Si), 30 krad(Si), and 50 krad(Si). The test devices were ALD111933-type n-channel floating gate transistors (FGMOSFET) with a threshold voltage of 3.3 V and normal operating temperature range of 0°C to 75°C. Each device package contained two n-channel FGMOSFETs.

1.2 Experimental Procedure and Test Method

Five devices were used in the experiment: one control device without irradiation and four devices irradiated at different total doses and temperatures. Specifically, two devices were irradiated at room temperature and two at elevated temperature. Detailed irradiation conditions are summarized in . All devices were irradiated under zero bias (all pins grounded). The dose rate was 5 rad(Si)/s for doses from 0 to 15 krad(Si), and 13.17 rad(Si)/s for doses from 15 krad(Si) to 30 krad(Si) and 50 krad(Si). Since the radiation response of floating gate transistors is essentially independent of dose rate [5], the effect of different dose rates on measurement data can be neglected.

Following irradiation to specified dose points, temperature stress tests were performed. Using a temperature chamber and HP 4140B test equipment, the drain-source voltage was set to 0.1 V while the gate voltage was swept from 0–6 V with a step size of 0.06 V. Devices were placed in the temperature chamber at four temperature points: 0°C, 25°C, 50°C, and 75°C. After reaching each target temperature, the device was held for 15 minutes before measuring its I_d–V_g relationship.

2. Results and Analysis

2.1 Device Radiation Response

The radiation response of device threshold voltage obtained using the method described in Section 1.2 is shown in [Figure 1: see original paper], where Figure 1(a) illustrates threshold voltage variation with cumulative dose and Figure 1(b) shows the radiation response sensitivity as a function of cumulative dose. As cumulative dose increases, the device threshold voltage shifts negatively, while the radiation response sensitivity decreases.

2.2 Temperature Effects on Floating Gate Device Electrical Characteristics

[Figure 2: see original paper] presents the relationship between device threshold voltage and temperature for both unirradiated devices and devices irradiated to 30 krad(Si). Threshold voltage was extracted using the constant current method, which directly obtains V_t from the transfer characteristic curve. The calculation formula for the drain current corresponding to threshold voltage V_t using this method is given in [5] as $= 100\,\mathrm{n}$. Threshold voltage exhibits a negative correlation with temperature, approximately linear, making it unsuitable for direct radiation dose characterization. The slope of linear fitting was used to approximate the temperature sensitivity of threshold voltage, yielding $k_1 = -1.74\,\mathrm{mV}/^{\circ}\mathrm{C}$ for unirradiated devices and $k_2 = -2.03\,\mathrm{mV}/^{\circ}\mathrm{C}$ for devices irradiated to 30 krad(Si). Irradiation alters the temperature dependence of threshold voltage, making circuit-level temperature compensation difficult and necessitating a simpler compensation approach.

2.3 Reference Voltage Selection and ZTC Point

Using the measurement method described in Section 1.2, we obtained the transfer characteristic curves of devices at different temperatures and identified the zero temperature coefficient point, as shown in [Figure 3: see original paper]. When the drain current is below the zero temperature coefficient point current, the corresponding gate voltage decreases with increasing temperature; when above this point, the gate voltage increases with temperature. In other words, higher temperatures yield smaller curve slopes and lower transconductance, reflecting the temperature dependence of carrier mobility. Since floating gate transistor threshold voltage serves as the parameter for radiation dose characterization, its temperature sensitivity affects measurement accuracy. To maximize suppression of temperature-induced interference, we selected the gate voltage at the zero temperature coefficient point as the readout voltage. The variation of this readout voltage with irradiation dose is shown in Figure 4: see original paper, while Figure 4: see original paper illustrates the measurement sensitivity as a function of total irradiation dose, demonstrating that sensitivity decreases slightly with increasing total dose.

2.4 Dose Effects on ZTC Point

[Figure 5: see original paper] shows the I_d–V_g curves measured at different temperatures for devices irradiated to various doses, with I_{ZTC} representing the zero temperature coefficient point current and the corresponding gate voltage serving as the readout voltage V_{ZTC}. Examination of dose effects on I_{ZTC} reveals minimal variation, with a slight increase as total dose accumulates. The readout voltage V_{ZTC} is also affected, which consequently impacts measurement accuracy. To investigate how dose affects the measurement precision of the zero temperature coefficient point method, we examined variations in V_{ZTC} at different doses and analyzed the resulting errors in radiation dose measurement. We found that V_{ZTC} for high-dose devices drifts slightly positive, causing the curves to diverge with temperature rather than intersecting at a common point. This deviation is characterized by the temperature sensitivity of V_{ZTC}, denoted as ΔV_{ZTC}. summarizes the impact of dose on measurement precision using the zero temperature coefficient point method, where ΔV_{ZTC} represents the measurement dose error. The table shows small measurement errors, not exceeding 1% across the operating temperature range even after irradiation to 50 krad, indicating ideal suppression performance and minimal impact of increasing dose on measurement precision.

2.5 Irradiation Temperature Effects on ZTC Point

[Figure 6: see original paper] illustrates the effect of different irradiation temperatures on the zero temperature coefficient point for devices irradiated to 15 krad(Si). The curves represent I_d–V_g characteristics of devices irradiated at elevated temperatures, with room-temperature irradiated devices serving as reference. Different irradiation temperatures produce noticeable differences in threshold voltage shift. Examining I_{ZTC} reveals that it increases slightly with irradiation temperature, again causing curve divergence rather than a common intersection point. This deviation is expressed as ΔV_{ZTC}, calculated using the same method as above. presents the impact of irradiation temperature on measurement precision, showing small errors not exceeding 1% across the operating temperature range, indicating minimal influence of irradiation temperature on the zero temperature coefficient point method's accuracy.

3. Discussion

3.1 Zero Temperature Coefficient Point Mechanism

The zero temperature coefficient point arises from mutual compensation between temperature-dependent variations in carrier mobility and threshold voltage. At a specific drain current, the corresponding gate-source voltage V_{gs} becomes temperature-independent. For an n-channel MOSFET providing drain current, the gate voltage can be expressed as [6]:

$$V_{gs} = V_T + \sqrt{\frac{2I_{dL}}{\mu_n C_{ox} W}}$$

where carrier mobility μ_n and threshold voltage V_T are temperature-dependent parameters that decrease with increasing temperature. Through derivation, the drain current can be expressed as:

$$I_d = \mu_n C_{ox} \frac{W}{L} (V_{gs} - V_T)^2$$

Assuming a linear temperature dependence for threshold voltage, $V_T(T) = V_T(T_0) + \alpha(T - T_0)$, where T_0 is the reference temperature and α is a constant, and mobility follows $\mu_n = \mu_n(T_0)(T/T_0)^m$ with $m \approx -2$, we derive the temperature-independent drain current:

$$I_{ZTC} = \mu_n C_{ox} \frac{W}{L} \left(\frac{\alpha T_0}{2m} \right)^2$$

This current is independent of temperature, and the corresponding gate voltage is also temperature-independent:

$$V_{gs} = V_T(T_0) - \frac{\alpha T_0}{2m}$$

These equations demonstrate that mutual compensation between the temperature effects of carrier mobility and threshold voltage can indeed produce a zero temperature coefficient point.

3.2 Total Ionizing Dose Effects on ZTC Point

Under zero bias conditions, irradiation dose causes a slight increase in I_{ZTC}, but the drift is minimal and has negligible impact on dosimeter measurement precision. This drift may be influenced by several factors: floating gate charge is "locked" within the nearly insulating oxide layer, making it essentially immune to temperature interference during measurement. Oxide trap charge annealing causes slight positive threshold voltage recovery and minor mobility increase, increasing curve slope. Conversely, irradiation dose increases interface state traps [11], causing negative threshold voltage shift and mobility reduction, decreasing curve slope. These two mechanisms compensate each other, offsetting transfer characteristic curve variations and resulting in minimal zero temperature coefficient point changes—similar to behavior observed in PMOS transistors [3].

3.3 Irradiation Temperature Effects on ZTC Point

[Figure 6: see original paper] shows that for the same irradiation dose, high-temperature irradiated devices exhibit greater negative threshold voltage shift than room-temperature irradiated devices. Normally, trapped hole annealing occurs through tunneling annealing and thermal excitation annealing, with thermal excitation dominating at high temperatures and accelerating oxide trap charge annealing [11], ultimately causing more negative threshold voltage drift during high-temperature irradiation. The zero temperature coefficient point current shows minor variations under different irradiation temperatures, with I_{ZTC} increasing slightly at high temperatures. This may occur because accelerated interface state trap growth at high temperatures causes positive threshold voltage shift and reduced I_d–V_g slope, while increased temperature enhances oxide trap annealing, causing negative threshold voltage shift and increased slope. During high-temperature irradiation, oxide trap charge annealing contributes more to I_d–V_g curve changes than interface state traps. However, since most holes enter the floating gate during ionizing radiation, the contribution of oxide trap charge annealing to positive threshold voltage drift is reduced, resulting in smaller positive I_{ZTC} drift.

4. Conclusion

This study investigated total dose irradiation and temperature effects on commercial n-channel floating gate transistors (nFGMOSFET) under zero bias conditions. Experimental results demonstrate that temperature significantly affects I_d–V_g curves, while the zero temperature coefficient point method effectively suppresses this influence. Both increasing total dose and elevated irradiation temperature cause slight I_{ZTC} increase, but the resulting measurement error remains small. Therefore, when measuring irradiation dose of floating gate devices at different ambient temperatures, the “zero temperature coefficient point” method can be employed to mitigate temperature effects.

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Author Contributions

Huang Wenyi: Experiment execution, manuscript drafting and final revision. Sun Jing: Guidance on experimental devices and procedures. He Chengfa: Research direction guidance. Liu Mingyu: Experimental assistance.

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