Effect of Electron Irradiation on 1700V 4H-SiC MOSFET Characteristics

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Aim

The aim of this work is investigate the influence of 4.5 MeV electron irradiation on static characteristics of commercially available 5 A/1700 V SiC power MOSFETs and describe related mechanisms of degradation.

Experimental

Devices under test (DUTs) were commercially available 5 A/1700 V SiC power MOSFETs C2M1000170D produced by CREE, Inc. Room temperature current to voltage (I-V) and capacitance to voltage (C-V) characteristics were measured in detail prior to the irradiation procedure. Unbiased DUTs were irradiated with different doses of high energy (4.5 MeV) electrons using the electron linear accelerator LINAC 4-1200. The irradiation was performed at room temperature with the total ionizing dose (TID) of 1, 5, 20 and 200 $\mathrm{kGy}_{(\mathrm{Si})}$. MOSFET's I-V and C-V characteristics were then re-measured and introduced radiation defects were characterized by deep level transient spectroscopy (DLTS).

Mechanisms of Degradation

1) Embedding of the positive charge

The initial decrease of threshold voltage V_{TH} is caused by positive charge trapped in the SiO_2 gate oxide layer. This shift in threshold voltage can be described by following formula:

$$\Delta V_{TH} = \frac{q \cdot g_0 \cdot f(E_{OX}) \cdot f_T \cdot D \cdot t_{OX}^2}{\varepsilon_{OX}}$$

where q is electronic charge, g_0 is number of generated e-h pairs ($8.1\mathrm{x}10^{12}$ $\mathrm{cm}^{-3}\mathrm{rad}^{-1}$), $f(E_{OX})$ is the fraction of generated holes vs. *e-h* pairs as a function of applied field, f_T is fraction of trapped holes vs. generated holes, D is dose in rads, t_{OX} is oxide thickness and ε_{OX} is permittivity of oxide.

Since MOSFETs were irradiated without voltage applied on the gate electrode, only 30% of generated e-h pairs were possible source of positive charge. The measured threshold voltage shift ΔV_{TH} = -1.6V@5kGy together with the estimated oxide thickness of 50 nm then gives **11% efficiency of hole trapping**.

2) Introduction of radiation defects

Electron irradiation introduced different deep-level defects. The spectrum was measured on 1700V 4H-SiC JBS diode. The unirradiated diode shows peaks connected with deep levels typical for as-grown SiC, namely the Z1/Z2 centers, which have total concentration of $7{\cdot}10^{12}$ cm^{-3}. The DLTS spectrum measured on the as irradiated sample than shows that the electron irradiation introduces different defects evidenced by a broad and dominant features labeled E1, E2, and E3 which are most likely given by superposition of several peaks (defects) with close activation energies. These defects form deep acceptor levels in the SiC bandgap, which compensate nitrogen shallow donors and cause carrier (electron) removal and significant decrease of electron mobility in the lightly doped drift region. The increase of the E2 centre concentration in the drift region of the DUT with irradiation dose shows a close correlation with the sharp increase of $R_{\mathrm{DS\_ON}}$. Lowering of electron concentration in the drift region is also evidenced by decrease of the drain to source capacitance C_{DS}.

Influence on I-V Characteristics

The effect of electron irradiation on electrical characteristics of irradiated MOSFETs can be divided from the application point of view into three parts:

1) In case of output and transfer characteristics, electron irradiation has improved ON-resistance approximately up to dose 20 kGy. This effect is more significant especially for lower gate-source voltages. This phenomena is caused by decrease in threshold voltage due to positive charge trapped in the SiO_2 gate oxide layer. ON-resistance decreases proportionally to $1/(V_{\mathrm{GS}}\text{-}V_{\mathrm{TH}})$.

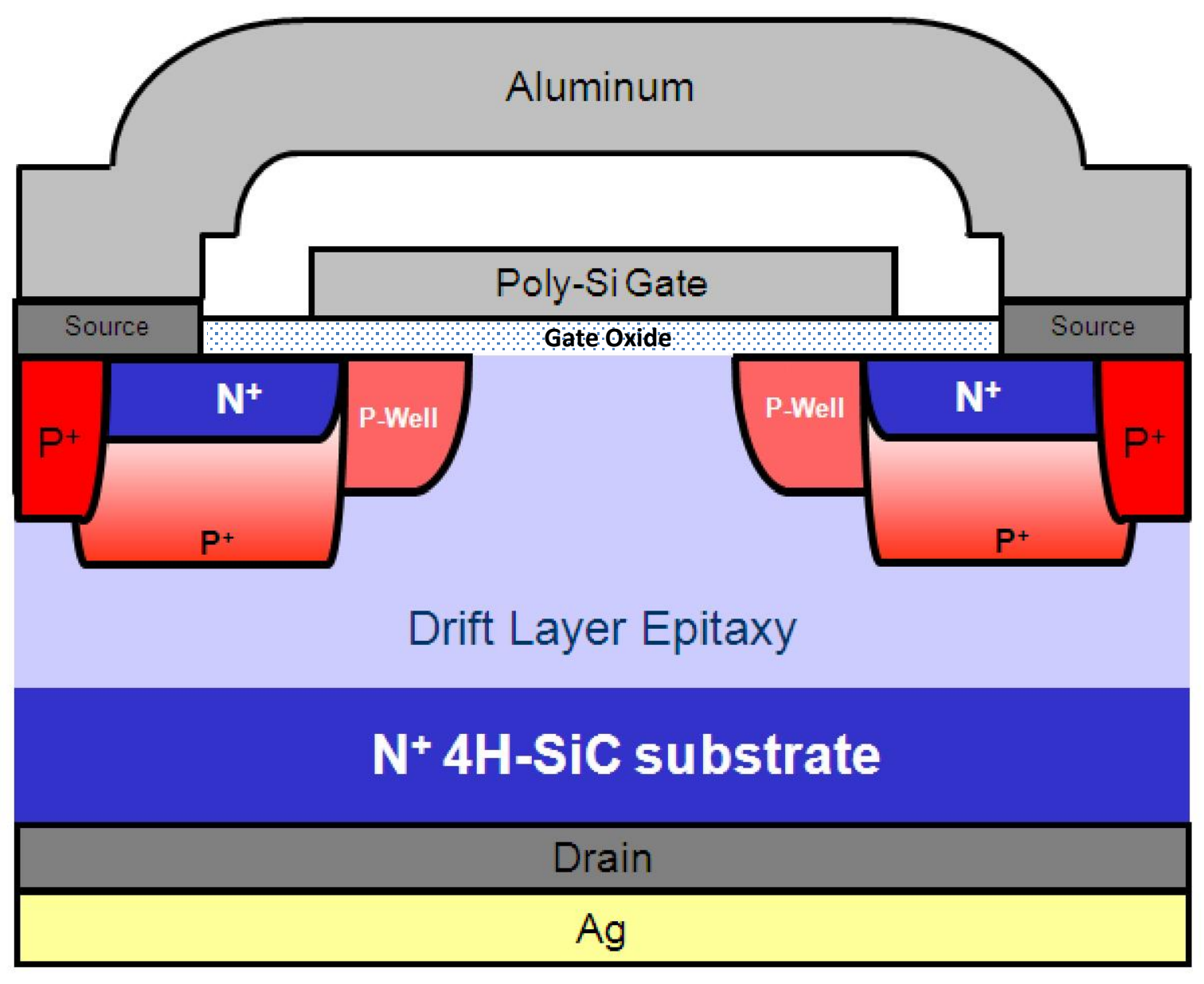
2) The effect of electron irradiation for doses above 20 kGy is opposite. Measured characteristics at dose 200 kGy shows increase of threshold voltage back to the original value and increase in ON-resistance about 40% against unirradiated devices. This effect can be probably caused by embedding of the negative charge into gate oxide (not by the development of the surface states at the SiO_2/SiC interface because of linear shift of subthreshold transfer characteristics and $C_{\mathrm{GS}}(G_{\mathrm{GS}})$ to V_{GS} characteristics) and decrease of electron concentration and mobility degradation in epilayer. It is expected that C2M1000170D MOSFET will lose quickly its functional capability when electron dose exceeds 200 kGy.

3) Situation in leakage and blocking characteristics is considerably different. Due to trapped positive charge in the SiO_2, leakage current for doses 5 – 20 kGy measured at V_{GS}=0 V is out of manufacturing specification. Reverse current 2 mA at V_{DS}=780 V was reached for dose 20 kGy. This effect can drastically reduce reliability of circuit operating at high voltage. Possible solution of this problem can be used negative bias on the gate. Gate bias of -1V has significantly improved blocking capabilities of MOSFETs (I_{D}=800 nA@V_{DS}=1700 V) back into manufacturing specification. Electron irradiation slightly increased blocking voltage from 2350V to 2360V. This effect can be connected with compensation of the lightly doped drift region caused by introduction of deep acceptor levels.

Summary

The effect of 4.5 MeV electron irradiation on static characteristics of commercially available 5 A/1700 V SiC power MOSFETs C2M1000170D was investigated. Results show that low doses of electrons cause a significant lowering of the threshold voltage which decreases rapidly and goes out of the specification already for *TID* > 1 kGy. This effect is caused by **embedding of the positive charge into the gate oxide**. On the other hand, DUT keeps its functionality and other parameters like $R_{\mathrm{DS\_ON}}$ are nearly unchanged. When electron dose exceeds 20 kGy, the threshold voltage start to move back to its original value, however, the ON-state resistivity increases and transconductance is lowered. This effect is connected with **introduction of radiation defects acting as deep acceptor into the low doped drift region**. Decrease in threshold voltage with irradiation dose increases MOSFET leakage while the drain to source breakdown voltage stays nearly unchanged. It is expected that C2M1000170D MOSFET will lose quickly its functional capability when electron dose exceeds 200 kGy.

Schematic Cross Sectional View



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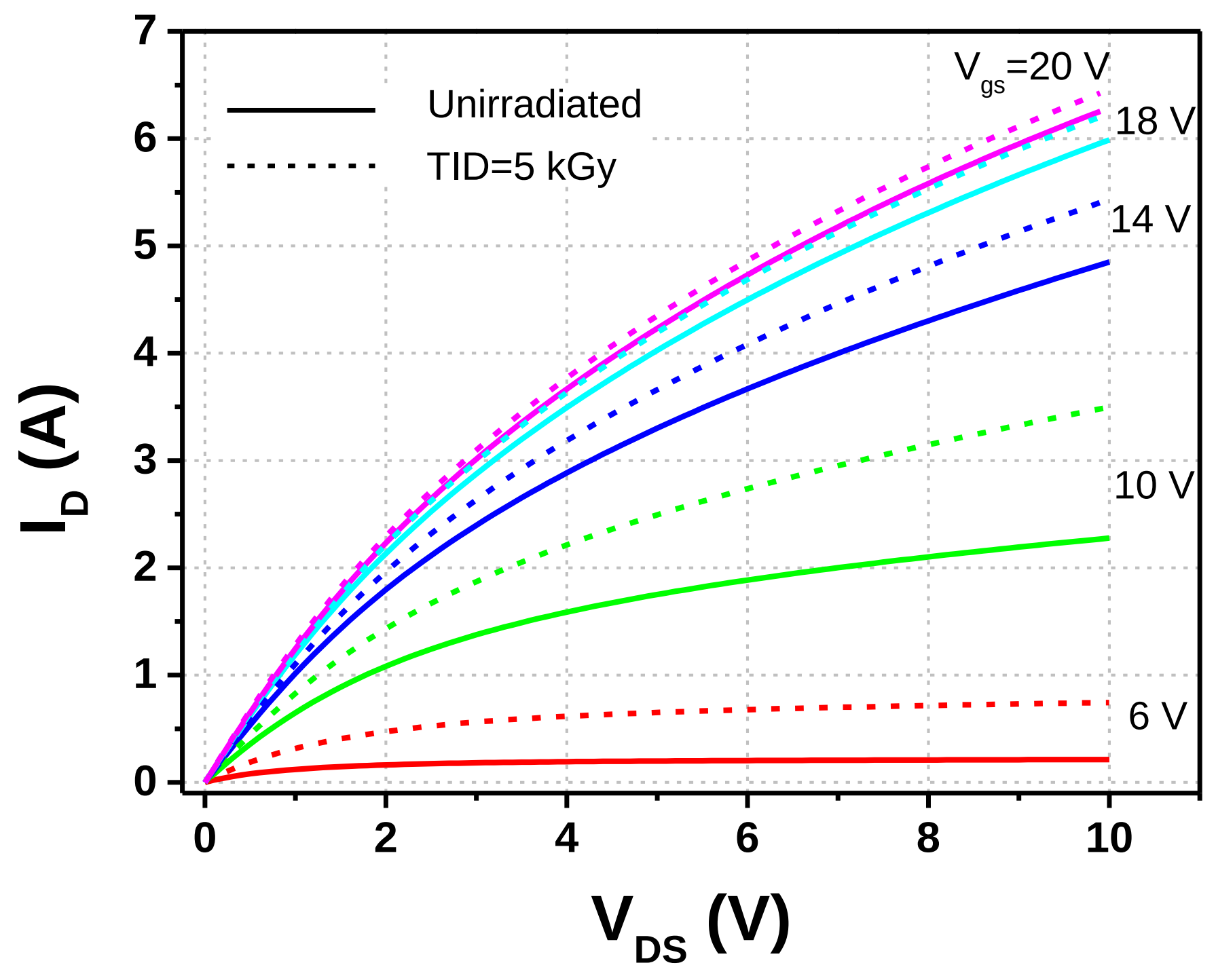
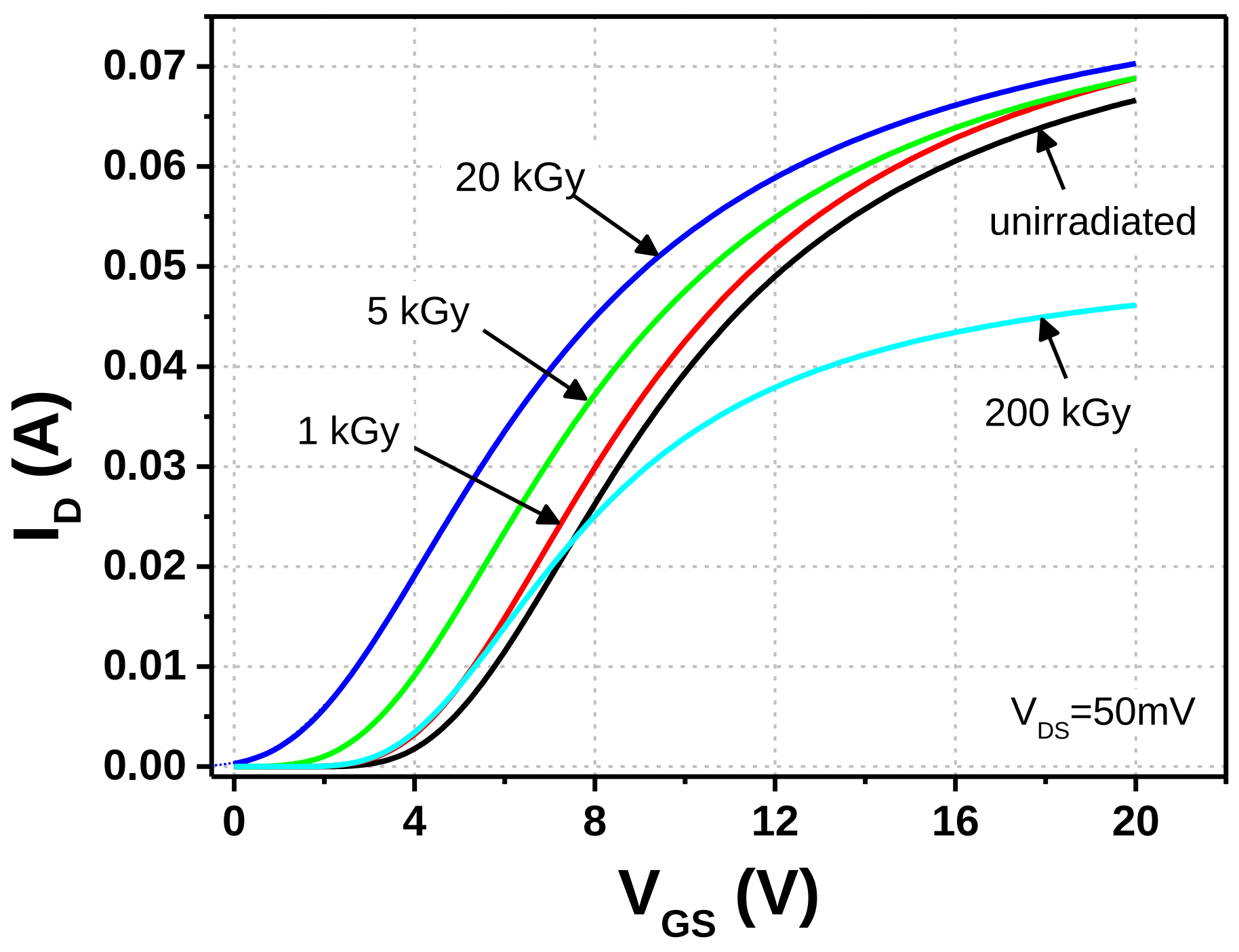
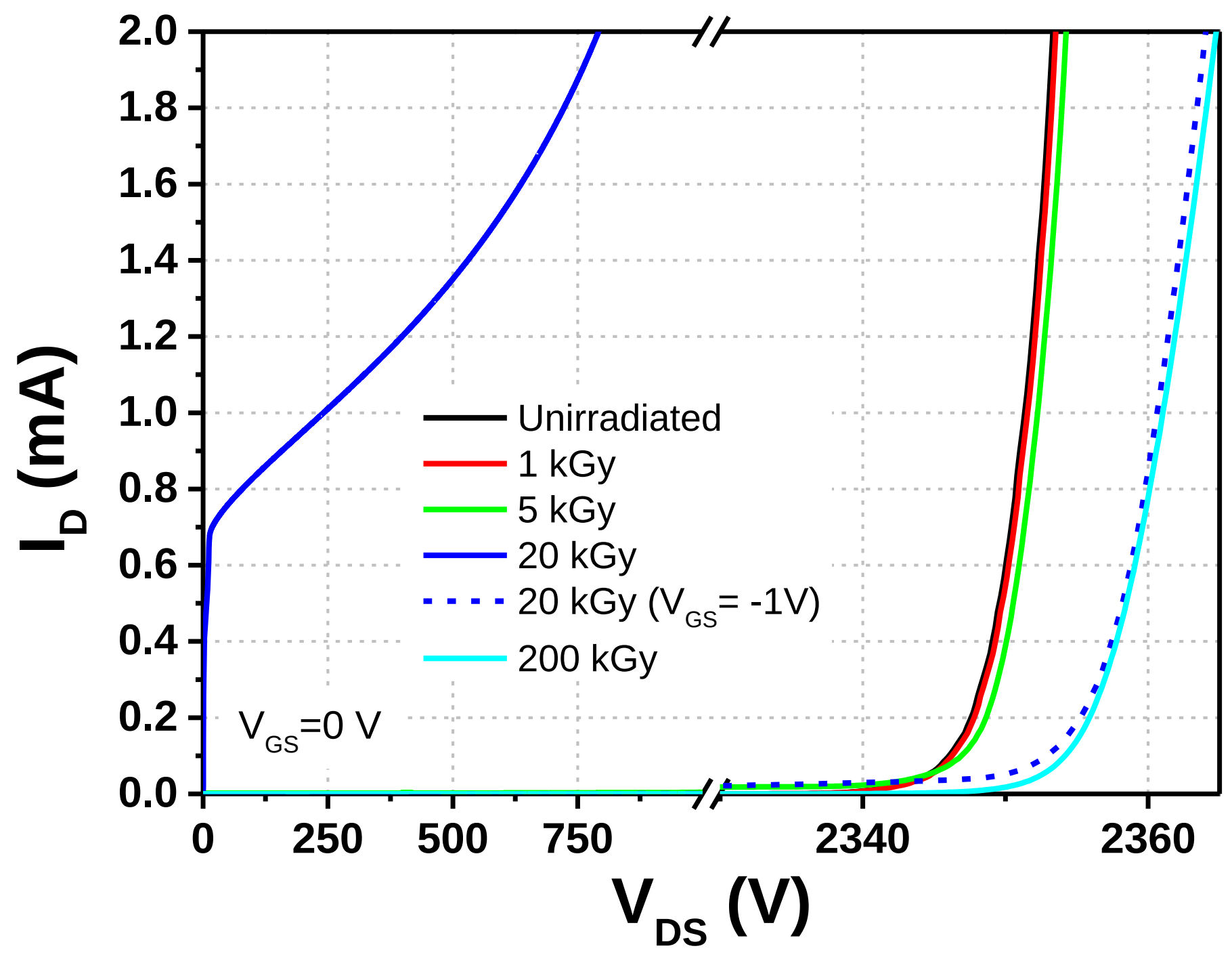
Output Characteristics



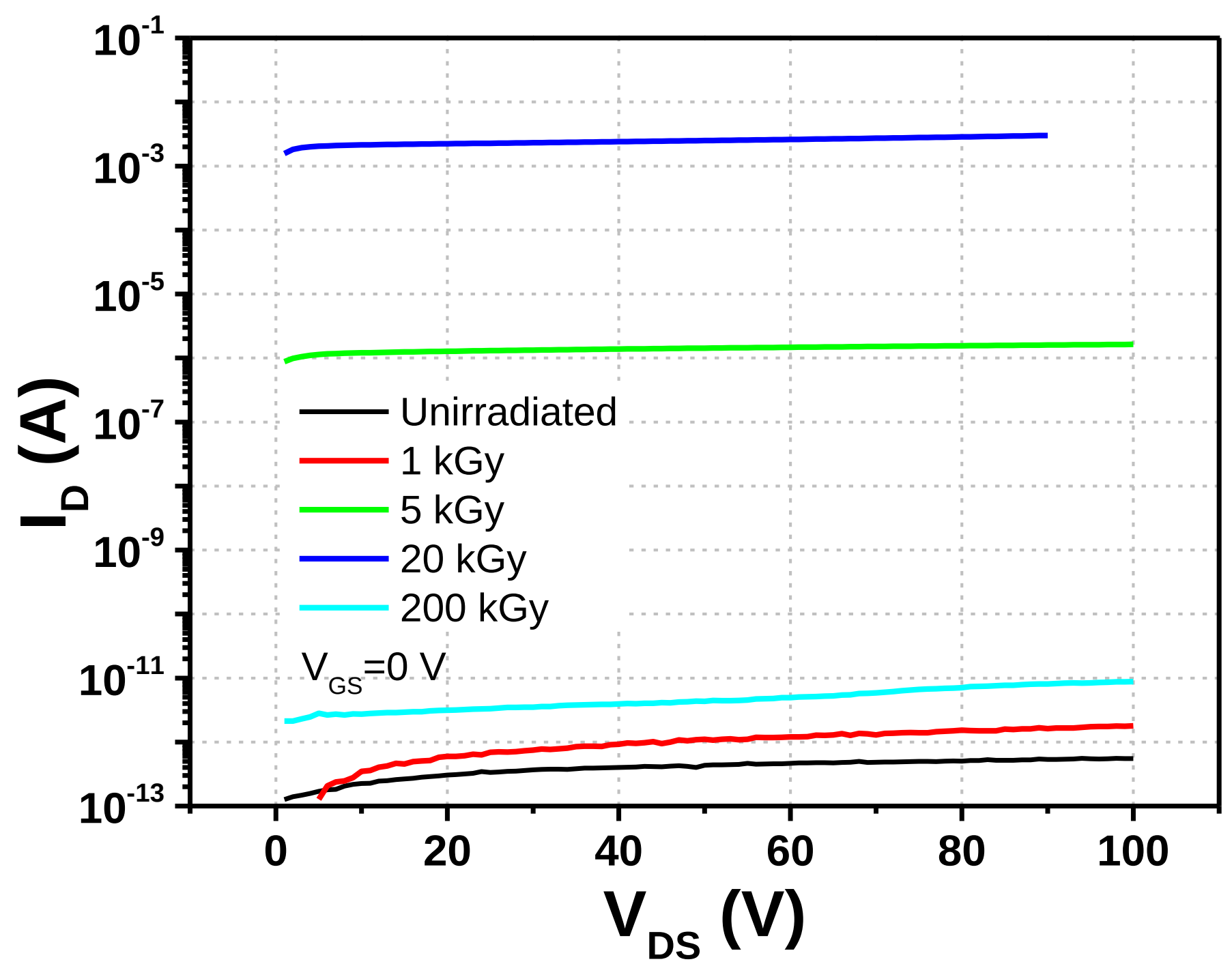
Transfer Characteristics



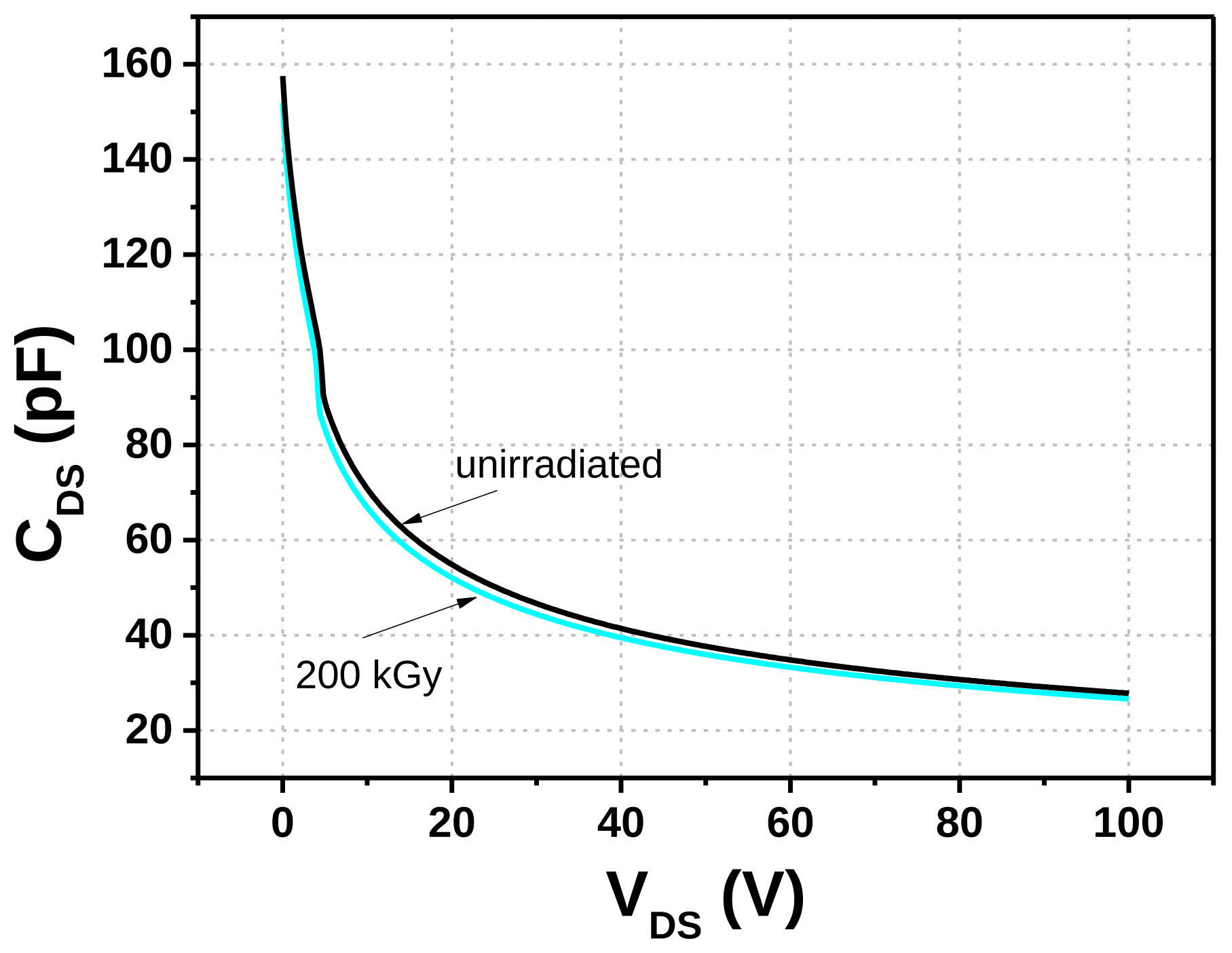
Blocking Characteristics



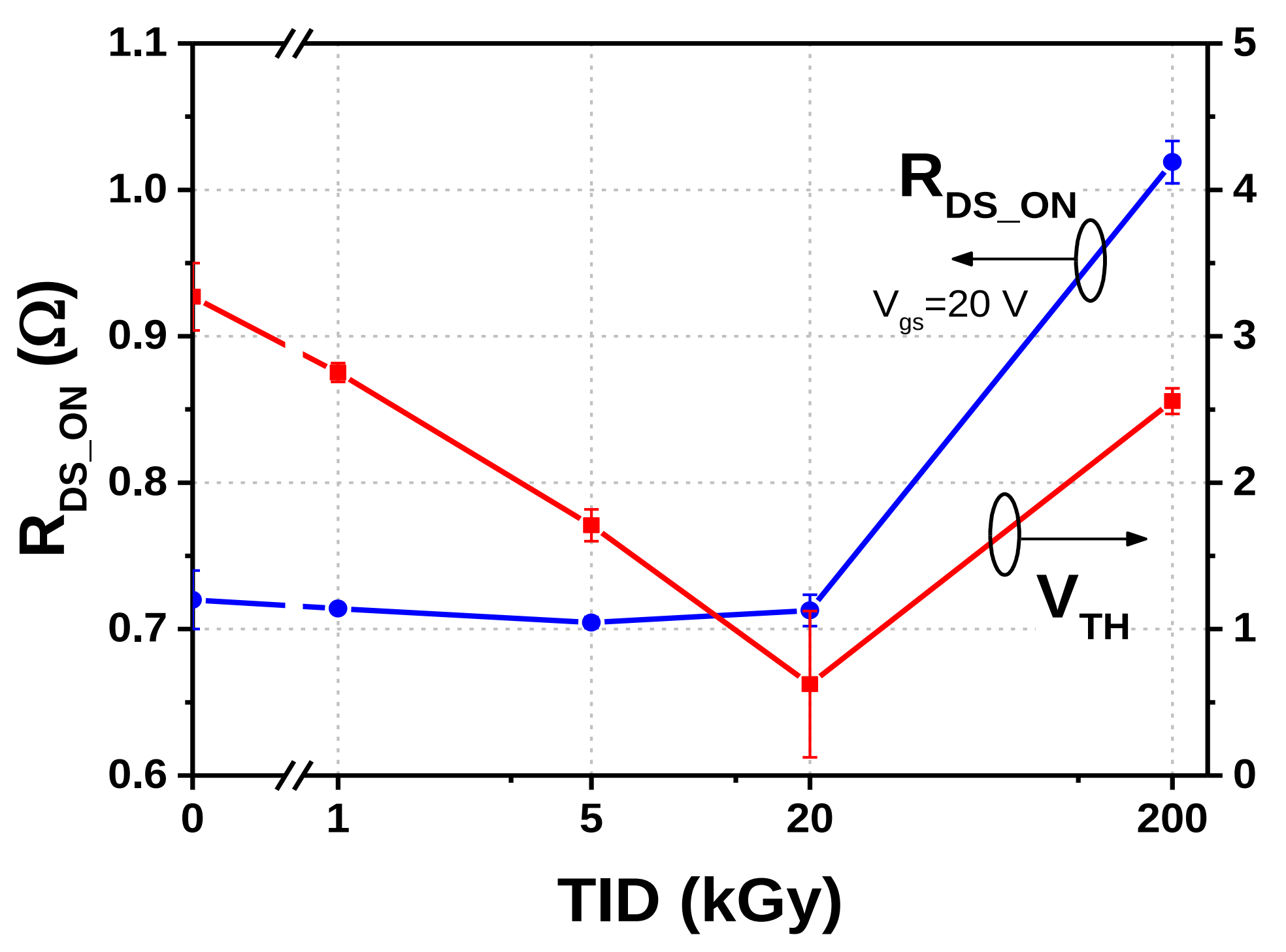
Leakage Characteristics



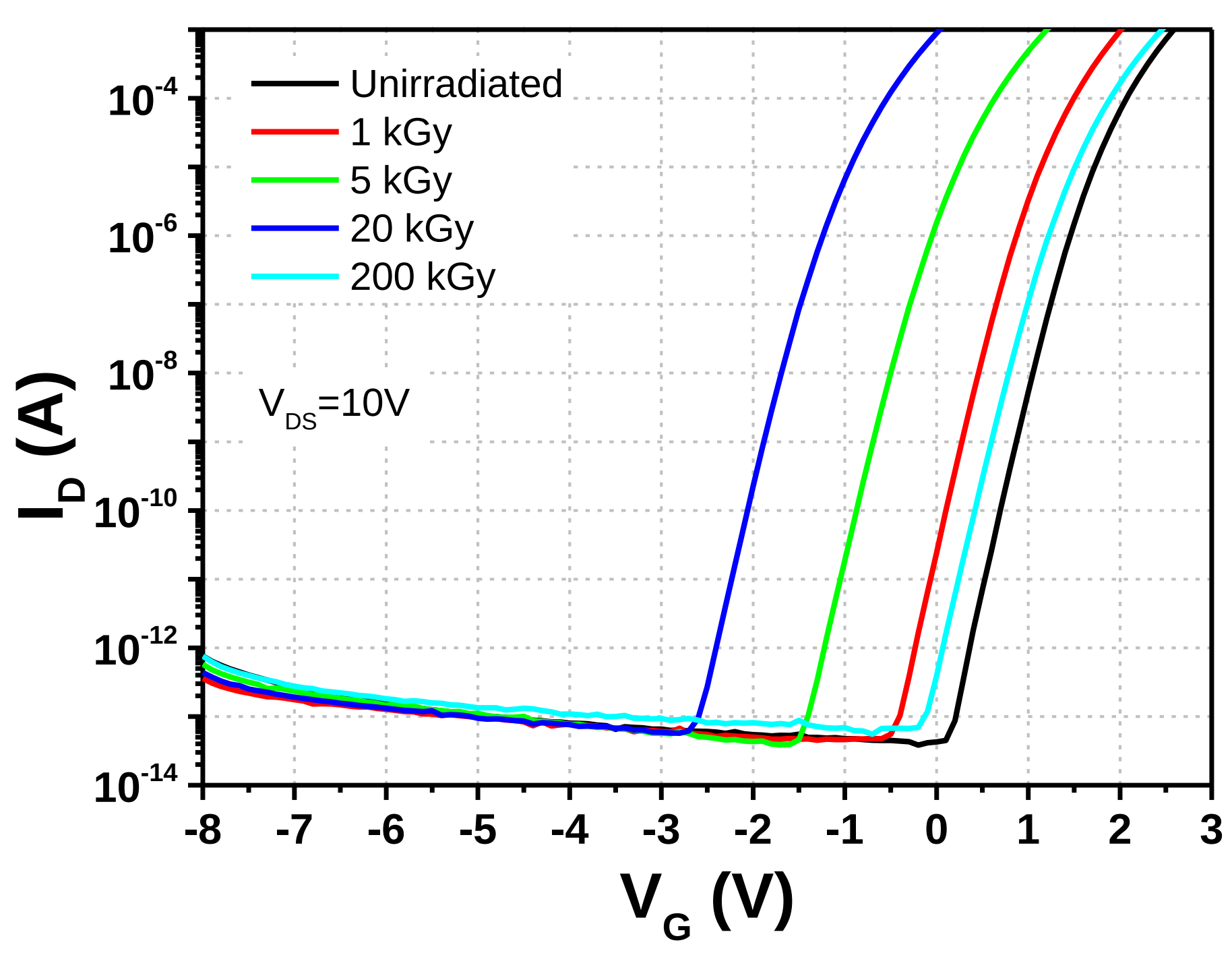
Effect of TID on Drain to Source Capacitance



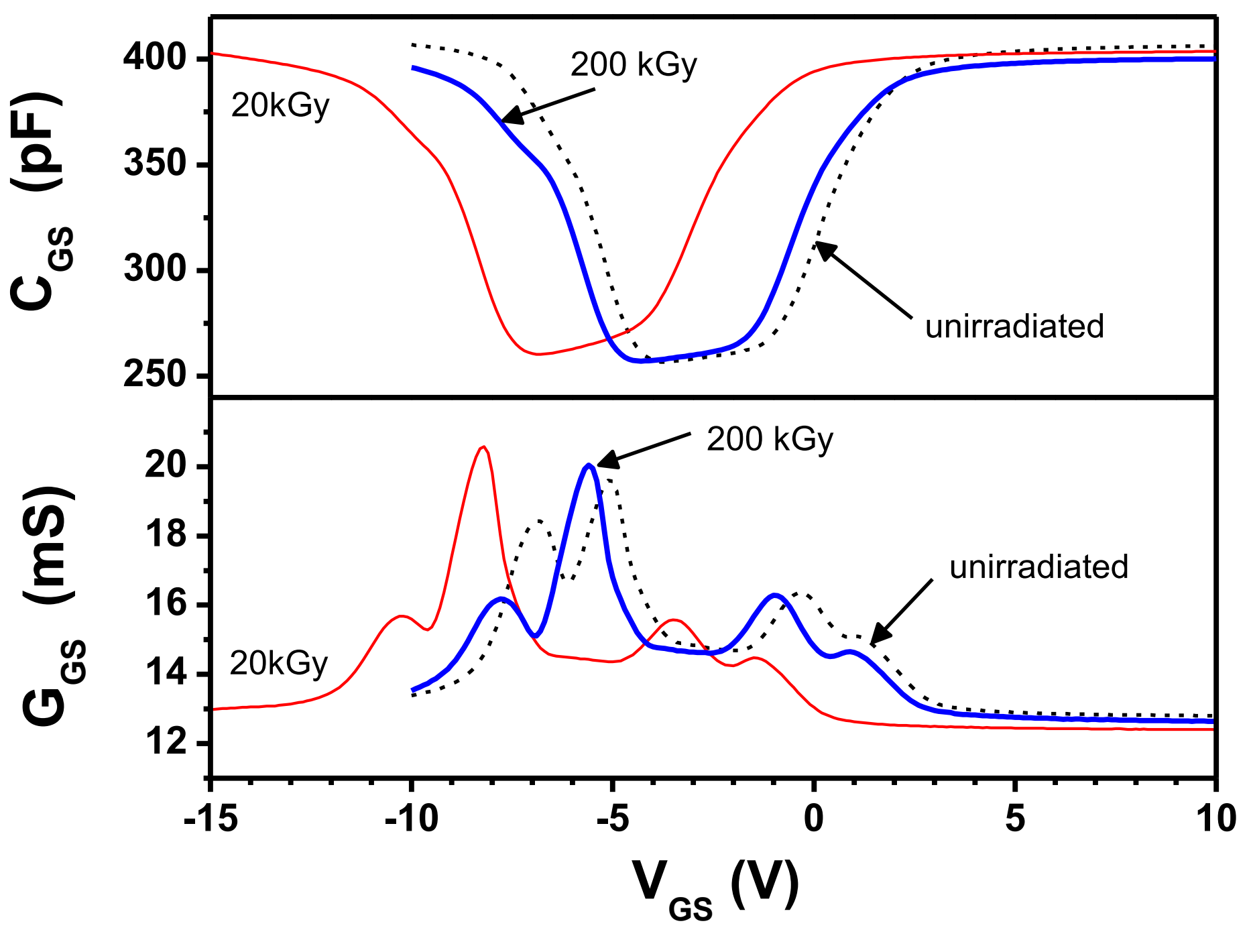
$R_{\mathrm{DS\_ON}}$ / V_{TH} versus TID



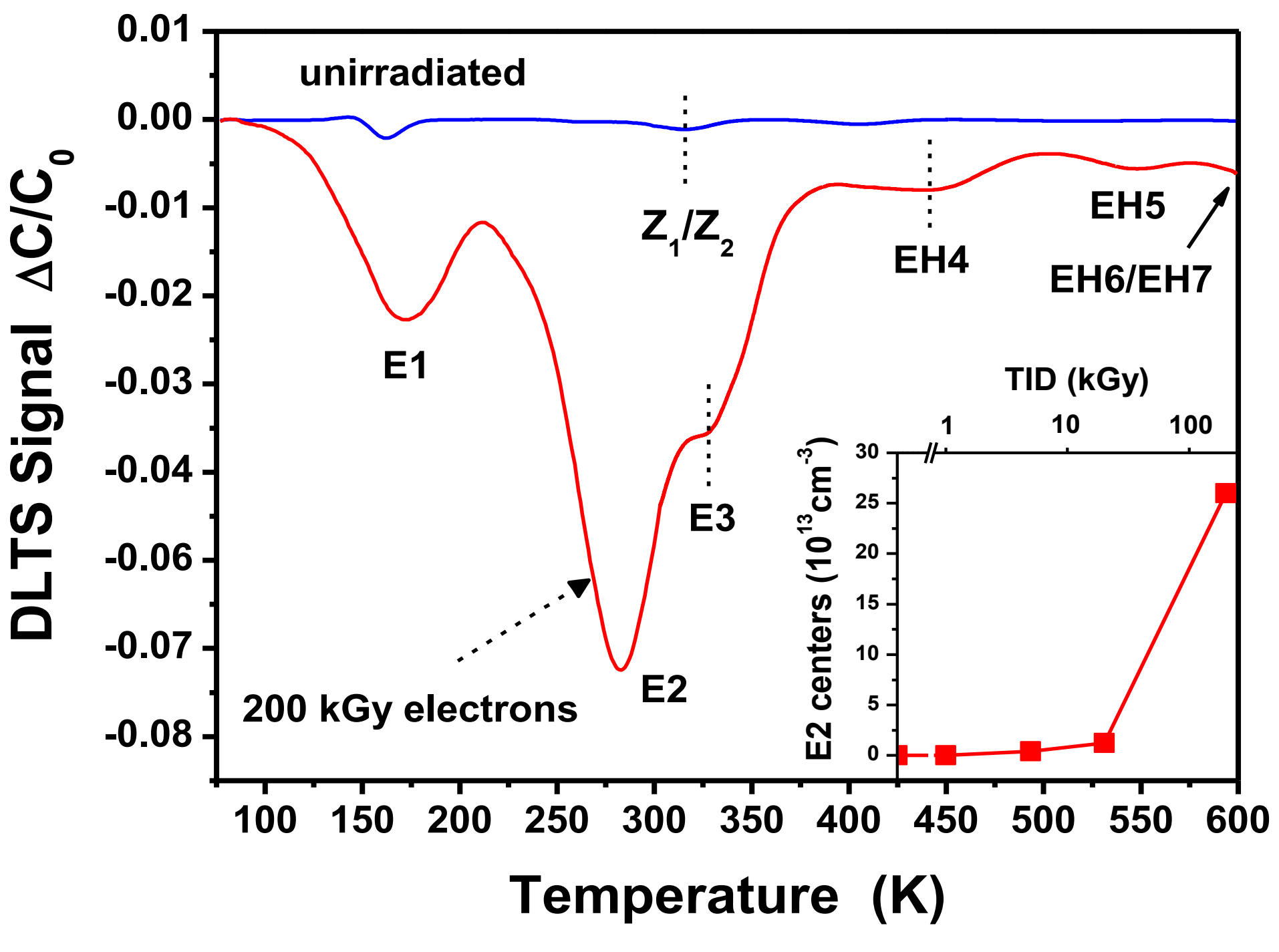
Subthreshold Transfer Characteristics



C_{GS}, G_{GS} versus TID



DLTS Spectra



This work was supported by the Grant P102/12/2108 of the Czech Science Foundation, the EU FP7 NMP 604057 project SPEED and the project SGS15/082/OHK3/1T/13 of the CTU Prague Grant Agency.