The Influence of Neutron Irradiation on Electrical Characteristics of 4H-SiC Power Devices

P. Hazdra, S. Popelka and V. Záhlava

Department of Microelectronics, Czech Technical University in Prague, Technická 2, 16627 Prague 6, Czech Republic

Motivation

Investigation of the effect of neutron irradiation on electrical characteristics of SiC MPS diodes and vertical JFETs, analysis of the influence of introduced defects on device characteristics and development of adequate simulation models.

Devices Under Test

Devices under test were 5A/1200V (C2D05120A) and 25 A/1700 V SiC MPS (CPW31700S025B) power diodes produced by Cree™ and vertical 1700 V normally-OFF trench SiC power JFETs SJEP170R550 from SemiSouth. All devices were fabricated on 4H-SiC epilayers with different thicknesses which were grown on heavily nitrogen doped N^+ SiC substrate. The N-epilayers were nitrogen doped in the range from 3 to 9×10^{15} cm^{-3}.

Introduced Defects

DLTS spectra show that fast neutrons introduce different electrically active defects evidenced by three broad peaks labeled E282/E304, E370/E400 and E563. Defects are homogeneously distributed in epilayer. Some radiation defects anneal out already at temperatures of device's operation (below 175°C), e.g., the unstable level E304 transforms to the well known Z1/Z2 centre (see the DLTS spectrum measured after annealing at 350°C). Introduction rate of defects is relatively high (1 to 4 cm^{-1}) and majority of them exhibits character of deep acceptor (electron) traps. As a result, neutron damage compensates epilayer donor doping. This is shown for devices with different concentration of nitrogen donors in the epilayer (8.4×10^{15} cm^{-3} JFET, 5.6×10^{15} cm^{-3} 1200V MPS and 3.2×10^{15} cm^{-3} 1700V MPS diode). The fluence which is necessary for total carrier removal is then dependent on device voltage class/epilayer doping. Depicted dependencies show that the slope of free carrier removal (carrier removal rate dn/dΦ) increases with epilayer doping (see the inset). This effect can be given by deactivation of nitrogen donors by radiation defects. The carrier removal rate follows linear dependence dn/dΦ(cm^{-1}) = 11.2 + 8×10^{-16} * N_D(cm^{-3}) where N_D is concentration of electrically active nitrogen donors. The first constant term is given by introduced deep acceptor centers while the second accounts for deactivation of nitrogen donors. Annealing at 350°C reduces the carrier removal rate of about 36% (see the dashed dependence for 1700V MPS diode).

Deep Levels Introduced by Neutron Irradiation

Level	Bandgap position (eV)	Capture cross section (cm²)	Identity
E282	E_C - 0.69	9×10^{-14}	Z1/Z2
E304	E_C - 0.72	7×10^{-14}	? (NI_2)
E370	E_C - 0.88	3×10^{-13}	$RD_{1/2}$
E400	E_C - 1.03	6×10^{-13}	EH4
E481	E_C - 1.08	3×10^{-15}	EH5
E563	E_C - 1.42	8×10^{-14}	RD_4

Effect on Device Characteristics

The irradiation decreases the free carrier concentration and mobility in the diode N-base (epilayer). As a result, the linear region of forward I-V curves becomes smaller and the current at higher bias decreases. This is consistent with an increase in the diode's series resistance R_S after irradiation. Sharp (up to four orders of magnitude) increase of R_S, which appears when compensation/deactivation reaches the doping of the epilayer (fluences 4.0×10^{14} and 1.7×10^{14} cm^{-2} for 1200 and 1700V diode, resp.), is then the most remarkable effect of neutron irradiation on MPS diodes. Neutron irradiation also degrades JFET transfer characteristics. In this case, the removal of charge carriers form the JFET channel, which grows with increasing neutron fluence, degrades the JFET threshold voltage and transconductance.

There is no significant impact of neutron irradiation on the blocking characteristics (see results for 1200V MPS diode). Only a slight increase in breakdown voltage and leakage current was observed for devices irradiated with the highest fluence of neutrons. Introduced defects act as acceptor traps and do not significantly influence electric field distribution (breakdown) since they are mostly neutral (empty) in the blocking regime of the DUT. Slight increase in leakage current in the breakdown area then given by trap-assisted tunneling which plays significant role at higher intensities of electric field.

Simulation of Irradiated Devices

The 2D model of the SJEP170R550 JFET was developed and calibrated in ATLAS device simulator. The effect of neutron and proton irradiation on electronic properties of 4H-SiC is similar. Both irradiations introduce deep levels behaving like electron traps. This allows for using of a simple model which substitutes all introduced deep levels in device simulation by only one dominant deep level with parameters of the Z1/Z2 centre [Vobecký et al., Solid.St. Electron 2014]. The effect of neutron irradiation was introduced by incorporating of four degradation mechanisms:

the removal of electrons and holes, $n = n_0 - K_N \cdot \phi$

the mobility degradation, $$\mu_n = \mu_{min} + \frac{\mu_{max} - \mu_{min}}{1 + \left(\frac{N_D + B \cdot K_N \cdot \phi}{N_{REF}}\right)^{\alpha}}$$

and the embedding of the surface states at the SiC/SiO_2 interface.

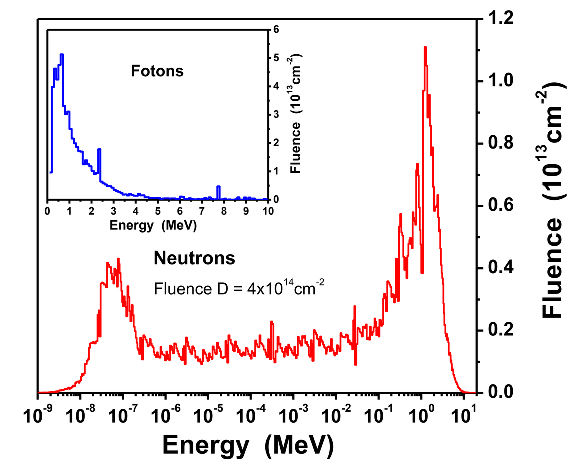
$$n_T = n_{T0} + K_{INT} \cdot \phi$$

Simulation of neutron irradiated devices showed a good agreement with experimental data. Simulation confirmed that carrier removal in the channel and drift region by acceptors centers introduced by neutrons is a main reason of SiC JFET degradation. Neutron irradiation decreases JFET parasitic capacitances. In this way, dynamic characteristics are improved and dynamic power dissipation lowered. However, the simultaneous increase in ON- state resistance significantly increases JFET's static power dissipation.

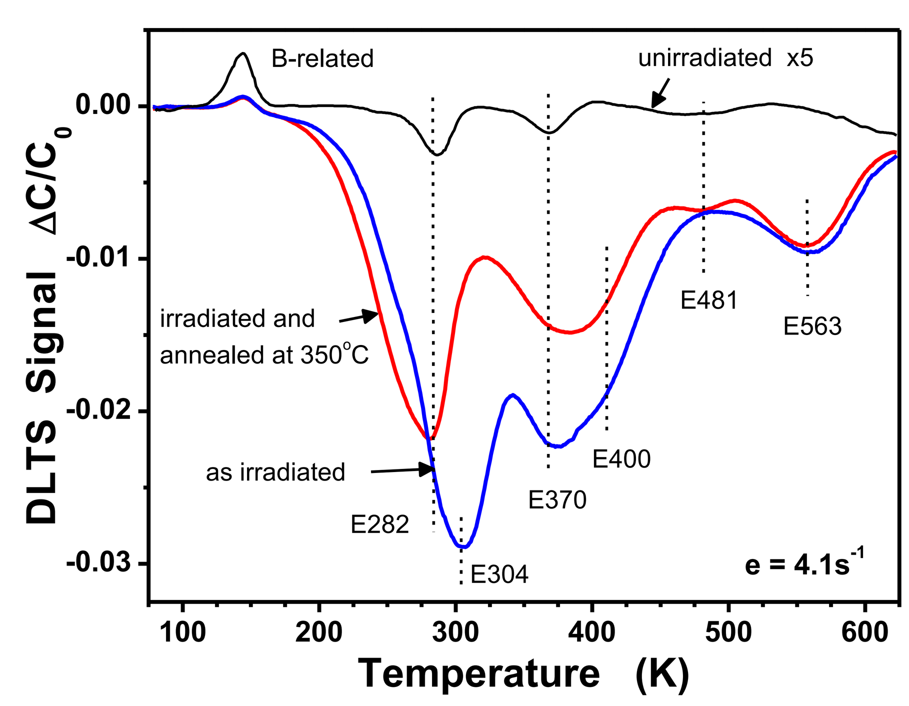
Irradiation

MPS diodes were irradiated by a fast neutrons in the mixed neutron/foton field of the LR-0 research (light-water, zero-power (1kW), pool-type) reactor in Research Centre Rez (CZ).

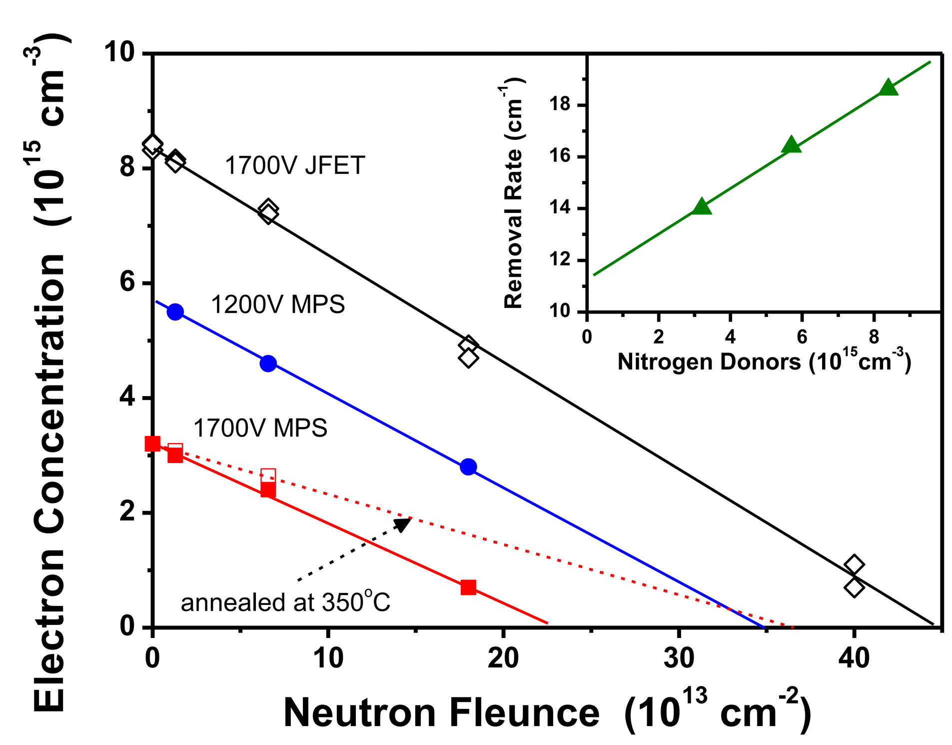
Group	Fluence (cm^{-2}) 1 MeV NIEL in Si
A	1.3×10^{13}
B	6.6×10^{13}
C	1.7×10^{14}
D	4.0×10^{14}



DLTS Spectra of Introduced Deep Levels

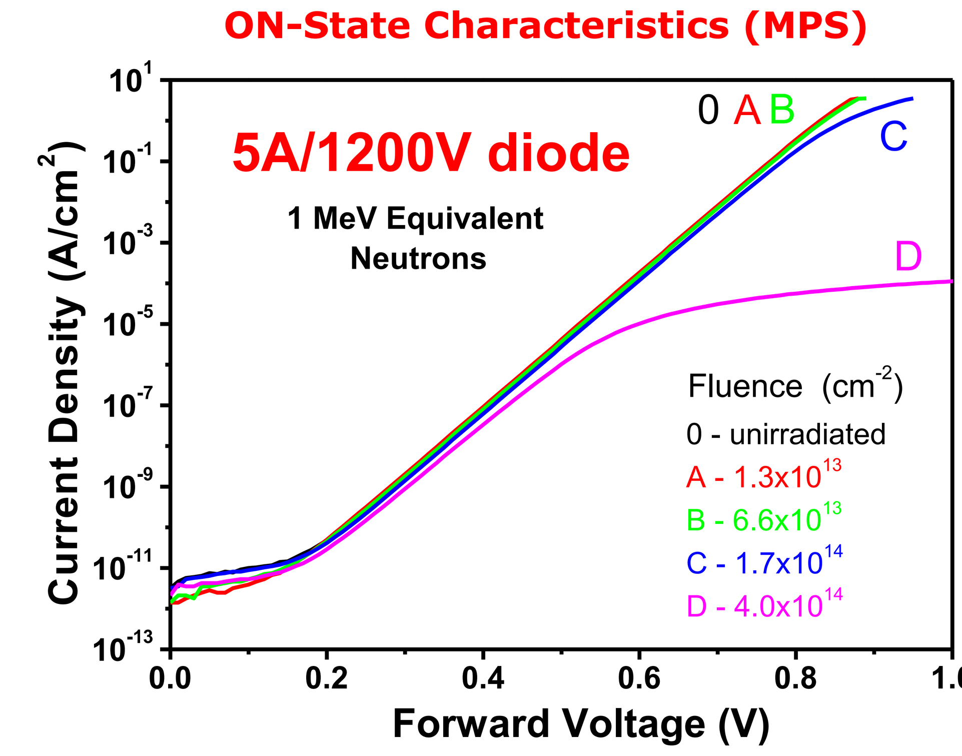


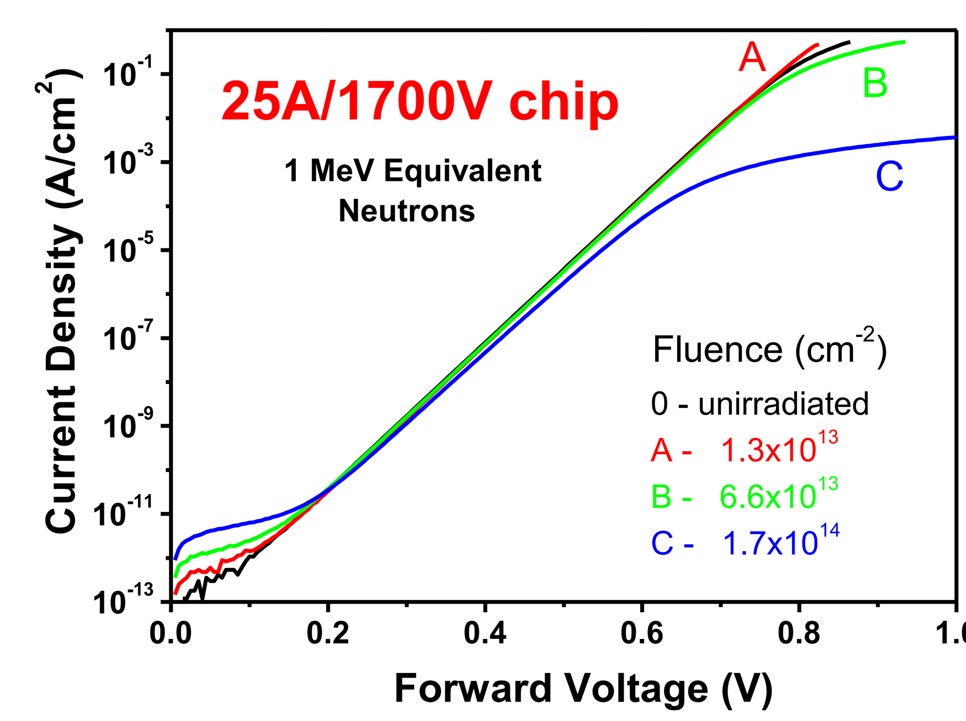
Carrier Removal by Neutron Irradiation



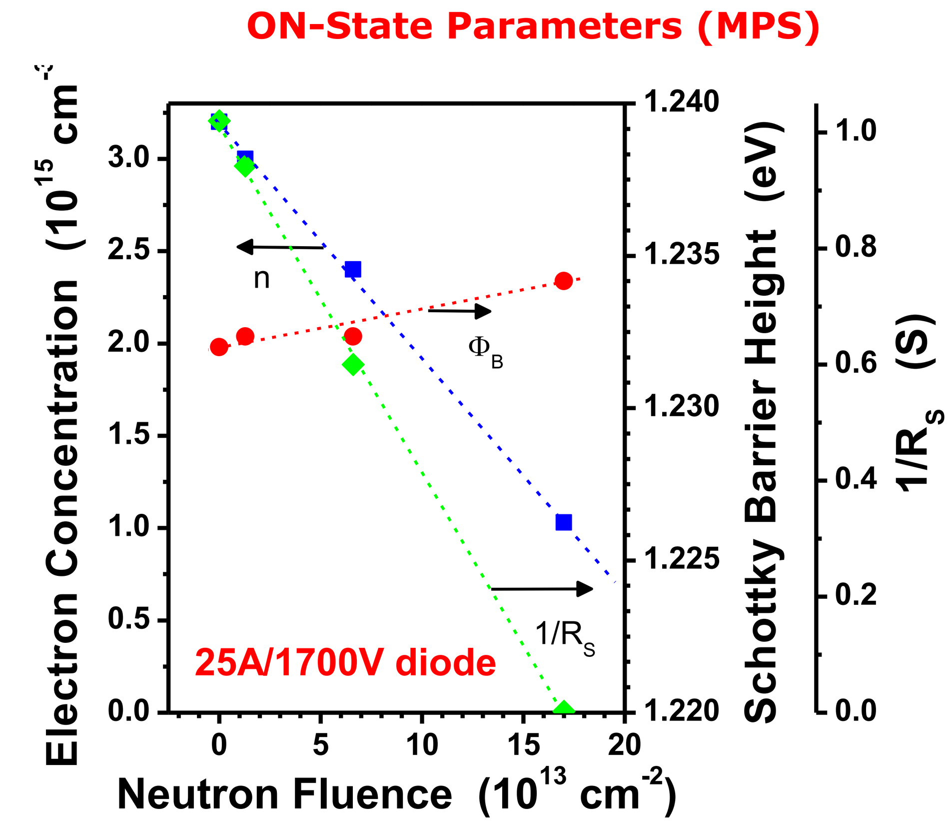
Neutron Irradiated MPS Diodes

ON-State Characteristics (MPS)

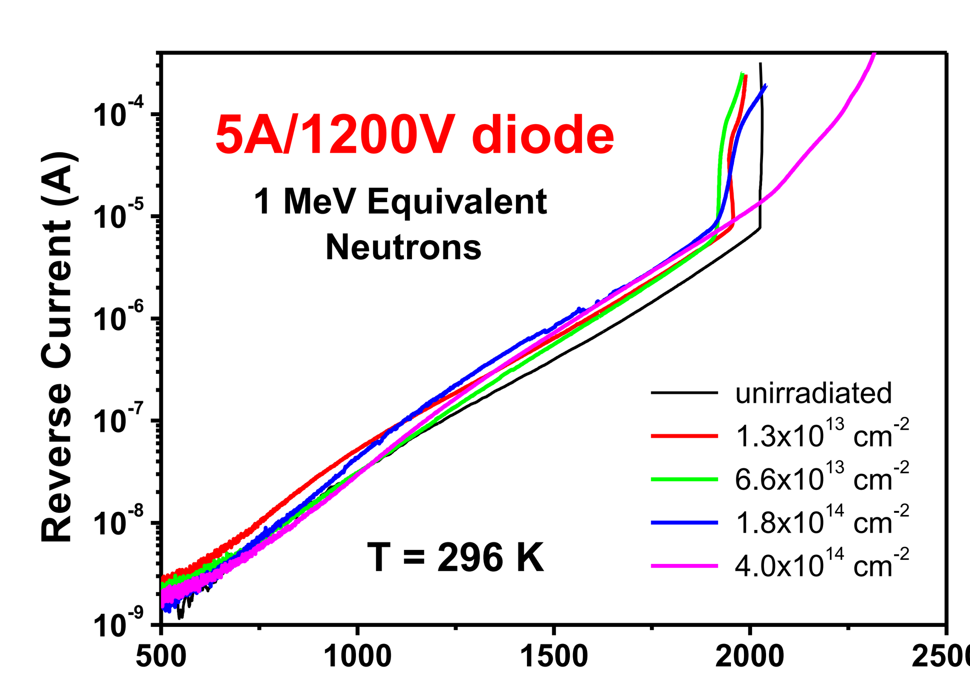




ON-State Parameters (MPS)

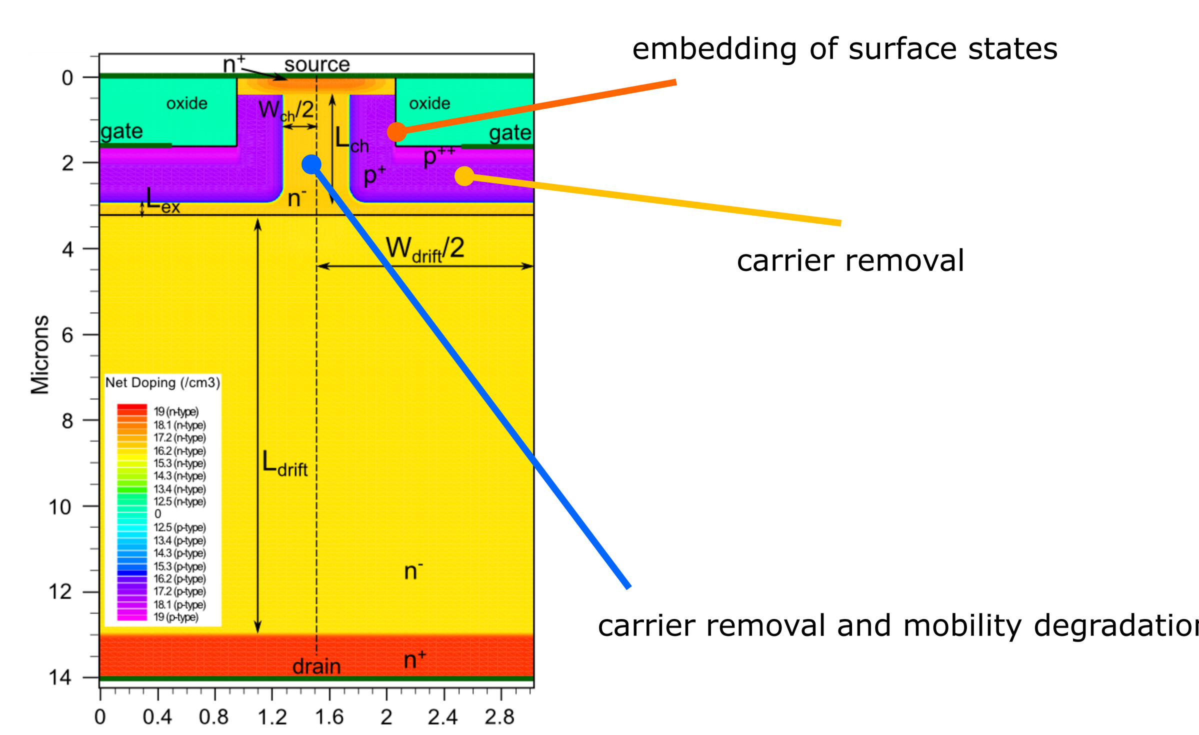


OFF-State Characteristics (MPS)

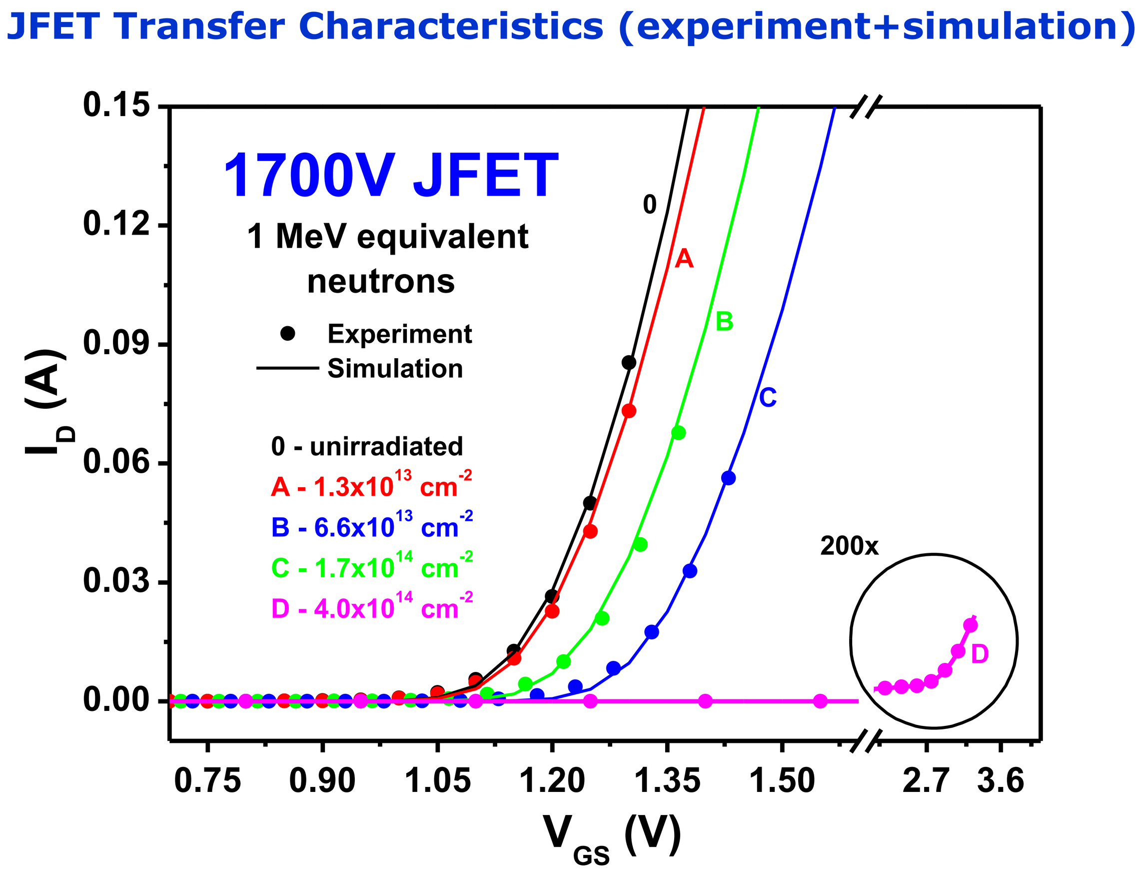


Simulation of Irradiated Devices

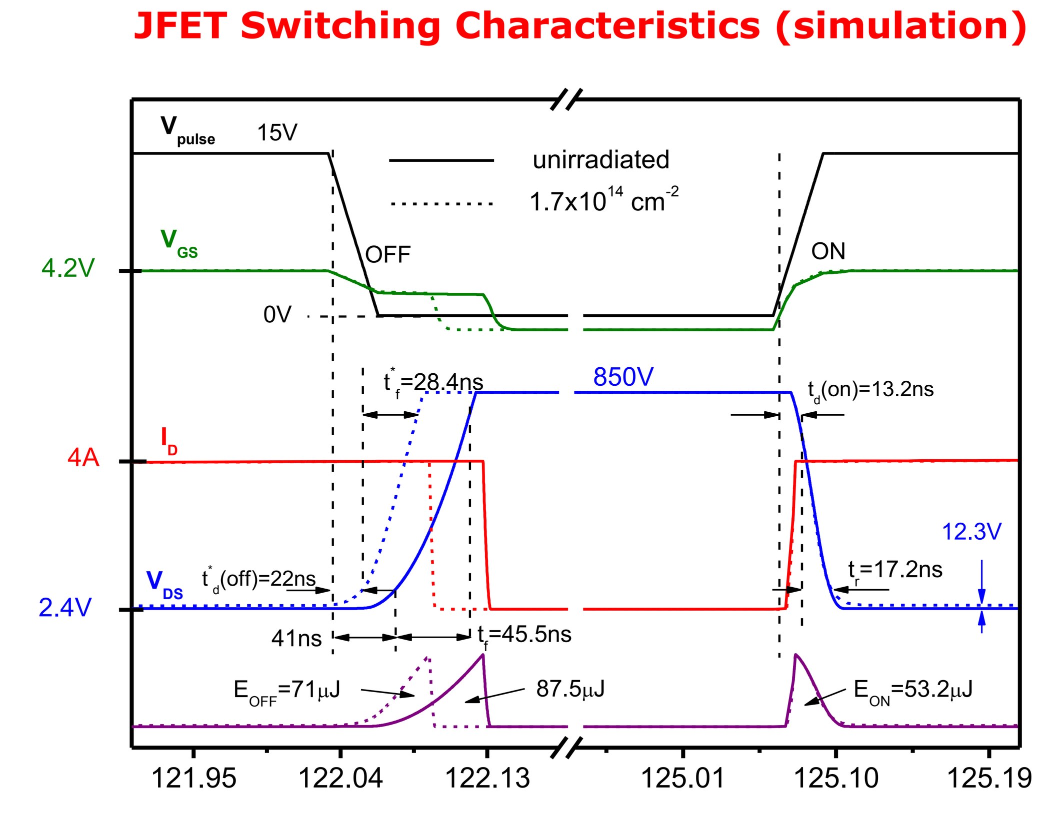
JFET Simulation Structure



JFET Transfer Characteristics (experiment+simulation)



JFET Switching Characteristics (simulation)



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