UPDATE OF SINGLE EVENT FAILURE IN POWER MOSFETS

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Abstract

This paper presents an update of the first 1994 compendium of single event test data for power MOSFETs. It provides failure thresholds from burnout or gate rupture for 01 devices of six manufacturers.

I. Introduction

Power transistor single event effects (SEE) test data obtained by Jet Propulsion Laboratory, The Boeing Company, Honeywell Space Systems Group (Clearwater, FL), The Aerospace Corporation, the group at the University of Arizona, NWSC (Crane, IN) and others have been included in this paper. Thus, this paper is a supplement to an original compendium presented in 1994 (Ref. 1.) The intent is to present a comprehensive set of MOSFET data from May, 1994, to May, 1996. It is believed, however, that additional data may be available that has not been published or brought to our attention. Contributors who desire inclusion in this and any future compendia should contact Don Nichols.

This **data** set includes **failure threshold voltages** (V_{DS} = drain-source voltage) for both single event burnout (SEB) and single event gate rupture or damage (SEGR or SEGD) of MOSFET power devices. There is no hard line of separation between power devices and lower power devices, nor is there a demonstrated immunity of the latter to SEE. There is some data (not shows) for SEB of npn bipolar devices but none for pnp bipolar devices. The bipolar data is still **very** limited and not included in **this** compendium.

The purpose of the present work is to supplement **the** data of Ref. I in order to:

(1) provide design engineers with operating voltage limits (max V_{DS} for a specified V_{GS}) of tested devices.

(2) identify unspecified process variables relevant to SEE response

(3) identify those parameters characterizing SEE response

(4) present trends that permit extrapolation from the existing data set.

II. Testing Approaches

Several possible testing approaches **have** been considered, but two are of fundamental importance. One approach attempts to measure the SEB/SEGR cross section vs V_{DS} of a device for a given test ion (or equivalently a given LET) for a fixed gate source voltage (V_{GS}) and temperature. This type of cross section should not be confused with the LET-dependent cross sections tabulated for soft errors in ICs. The transistor cross section equals zero at lower V_{DS} and rises very rapidly only at its threshold V_{DS} (almost like a step function); then tends to level off at somewhat higher V_{DS}. So far, few experiment have extended the data far beyond threshold, but such data is mentioned when known.

To obtain SEE rates for a specified environment and operating condition (defined by temperature and V_{GS}), one must perform the same experiment for several other ions to establish the voltage threshold and cross sections above each of the voltage failure thresholds. This approach requires a large sample size and still does not provide an adequate basis for calculating the device upset rate. All of the preceding cross sections must also be repeated for angles of beam incidence greater than zero, unless a plausible angle dependence has been provided.

The second approach seeks simply to identify the threshold voltage V_{DS}(th) for failure for a given ion (usually Ni/Fe or Br/Kr), a fixed V_{GS} and temperature. The selected ion should represent a realistic worst case for the environment. Ni or Fe ions at normal angle of incidence is a realistic worst case, because there is no increased susceptibility from grazing angle ion strikes as there is for integrated circuits. The latter approach indicates a voltage operating limit to the designer who can apply a derating factor to his operation, but it also offers little chance to estimate the failure probability if one chooses to operate above threshold.

The data tabulated here in one. extended table presents threshold V_{DS} for several groups of ions at a few selected gate source voltages V_{GS}, following the second (recommended) approach. Some theoretical determinations indicate the effect of varying V_{GS} (related to oxide field) for a fixed drain-source voltage. A nearly standard technique for measuring the threshold V_{DS} consists of the following steps:

(1) Prior to any irradiation, measure the drain source current at rated BV for $V_{GS}=0$, or alternatively measure the actual breakdown V_{DS} for the same conditions. One should also measure the gate-source current at maximum rated gate voltage (usually 20 V) for $V_{DS}=0$. These measurements establish the normal operating currents.

(2) Choose a single gate voltage V_{GS} (start with the least susceptible zero voltage) and hold it constant for each subsequent irradiation step, for successively larger V_{DS}. At the end of each irradiation step of, say, 10^5 ions/cm^2, change the bias conditions back to those used in step (1) to again determine the two currents I_{GSS} and I_{DSS}.

(3) Failure may occur as either (1) SEGR as evidenced by a large permanent increase in gate current ranging between a fraction of a milliamp up to the circuit-imposed limit (say, 10 amps) or (2) SEB (burnout) evidenced by a short across source and drain as well as a gate short.

(4) Delayed Failures-- On occasions JPL and other test organizations have seen delayed types of SEGR. On some occasions, the gate currents increased to ~1 mA during irradiation and then increased again to the circuit limit during post-beam tests where, as always, V_{GS} was reset to 20V. Another type of SEGR failure occurs when the drain-source voltage is incremented for the next test. Some experimenters have modified the abrupt change to max gate-source voltages between irradiations, by ratcheting V_{GS} upward in steps.

III. Supporting Studies

Several collateral tests have been performed by now. Nichols et al (2), Fischer (3), Tastet (4), Mouret (5) and Titus (6) have demonstrated that higher grazing angles of ion incidence have less effect on SEB and SEGR than normally incident irradiation. Hence the complications involved in calculating SEE rates by dealing with an effective LET vs incident ion angle are simplified. (In actuality, there is no known formal method for calculating rates under these conditions for a specified environment except to take a very simplified worst case in which all strike angles are assumed to affect the device equally.) High temperature tests have been performed (2,7, 8) showing that SEB is greatly reduced at higher temperatures due to phonon interference with the avalanche burnout mechanism. In contrast, high temperatures tend to promote SEGR in a few cases, but not in others (6).

It is noted that most transistors that differ only by die size (e.g. by having a different number of the same size transistor elements or cells) have similar breakdown voltages as expected. However, there are a few occasions when such devices yield widely different SEE results. It is postulated that the dielectric oxide breakdown voltage (an uncontrolled parameter) may be responsible for wafer-to-wafer and device-to-device variability to SEE.

IV. Organization and Scope of Data

This paper presents SEB and SEGR data for MOSFETS in Table I for all known new data taken up to May, 1996-- as marked with an asterisk in column 1. Data are also included from earlier tests for those parts that are closely related to parts for which new data are tabulated, so as to put the new data in context. Closely related device data are those lying on a contiguous row in the table's data entries. It is noted that many tests are repeated in the data sets-- useful for showing consistency in most cases, but possibly cost ineffective. Some data are taken at an elevated temperature, which consistently shows a higher threshold voltage when SEB is the failure mode. Data sets by 11SS are particularly useful in comparing the two temperatures with a switched gate bias. Dynamic testing has a dramatic effect in forestalling burnout failures, by interrupting the rather slow failure modes.

Six manufacturers are represented in this second set, which broadens the manufacturer base beyond that reported in Ref. 1-- primarily for International Rectifier (INR) and Harris (HAR). Most data are for commercial parts, but there are some new "rad-hard" technologies.

The data are grouped in rows by device manufacturer. Within each manufacturing group, devices with the lowest breakdown voltage are listed first-- first n-channel and then p-channel. Devices that are very similar, or the same devices tested with different conditions (e.g. V_{GS}) are grouped in touching, adjacent rows. The columns list manufacturers, device number(s), channel type, and test sample size. It is observed that samples are seldom large enough to provide rigorous statistics, nor a characterization of maverick behavior that is occasionally noted. Most data, however, are fairly repeatable. Subsequent columns list the rated breakdown voltage (BV) and gate-source voltage V_{GS}.

The next five columns group the data according to test ions. Single voltage entries in the ion columns show a failure voltage; a slashed pair show a pass/fail voltage threshold. The first column is for low-LET ions having LETs less than that of the dominant Ni/Fe/Co/Cu group included in column two. This first group is useful in judging the adequacy of postulated theories (See for example, ref. 3). It is now often accepted that a characterization with a single ion of the second group may be all that is needed for project requirements. This view is supported by two facts: (1) those heavier ions having a higher LET have fluxes in outer space two or three orders of magnitude smaller than that of the Ni/Fe group, and (2) there is no need to account for enhanced effects from grazing-angle collisions having a high "effective" (angle-dependent) LET. The third group in the table includes Br and Kr (LET=37 MeV/mg/cm^2), traditional high LET ions at the Brookhaven Van De Graaff (BNL) and U. C. Berkeley 88-inch cyclotron (88), respectively. The fourth group includes the highest LET ions easily available at the aforementioned facilities. The fifth column includes data from very high energy (10-100 MeV/amu) facilities: the Berkeley Bevalac (now defunct) and GANIL (France). It is this last group of ions that present some inconsistencies with the lower energy LET characterizations, for reasons that have not yet been fully explained. Some of this column set are empty for this update;

they are nevertheless retained to be compatible with the larger data set of Ref. 1

The remaining set of columns provide the failure mode, the test group, test date, ion facility and "Remarks." It is useful to know that INR uses 7000 and 8000 numbers to specify n-channel devices with 100 Krad and 1 Mrad total dose tolerance, respectively; both INR and Harris use 9000 numbers for p-channel devices. The second INR mfr number (or the *first* for three-digit part designations) relates to the breakdown voltage. The next number is related to the die size-- the larger this number, the larger the die size and (usually) the larger the number of individual cells. INR's letter "H" in the third place from the left of the letter prefix means that the devices are especially designed to be radiation resistant to total dose. It turns out that such devices are also very resistant to single event effects as well. The fourth letter of INR (which may be "H") and the third letter of HAR devices is a package designation not expected to affect SEB/SEGR data. Harris denotes rad hard tolerance with a suffix after the device number; R= 100 Krad and H= 1 Mrad. FSF is a recent Harris designation for their SEE hard technology -- a claim defined by the data given in Table 1.

VI. Conclusion

This updated compendium of SEE effects (SEB and SEGR) in power MOSFETs can be combined with the. data presented in Ref. 1 to provide a useful data base for designers of satellite and space systems. Some extrapolations may be warranted, and some cautionary observations are also provided. Testing with only one ion is often acceptable for system requirements; the reduced effect of incident ions at oblique angles presents an important simplification for parts selection if parts are available that meet the measured threshold voltage failure levels for the highest-LET population of any consequence in space-- the Ni/Fe group.

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References

(1) D. K. Nichols, K. P. McCarty, J. R. Coss, A. Waskiewicz, J. Groninger, D. Oberg, J. Wert, P. Majewski, R. Koga, "Observations of Single Event Failure in Power MOSFETs", IEEE Radiation Effects Data workshop," p 41, (Dec, 1994)

(2) D. K. Nichols, James R. Coss, Kenneth P. McCarty, "Single Event Gate Rupture in Commercial Power MOSFETs," *RADECS93* (accepted for publication).

(3) T. Fischer, "Heavy-Ion-Induced Gate-Rupture in Power MOSFETs," *IEEE Trans. on Nuclear Science*, NS-34, No. 6, 1786 (Dec., 1987).

(4) P. Tastet & J. Garnier, "Heavy Ion Sensitivity of Power Mosfets," *RADECS91*, p 138 (1991)

(5) I. Mouret, M. Allenspach, R. D. Schrimpf, J. R. Brews, K. F. Galloway & P. Calvel, "Temperature and Angular Dependence of Substrate Response in SEGR," IEEE Trans. on Nuc. Sci., NS-41, No. 6, 2216 (Dec., 1994)

(6) J. L. Titus, C. F. Wheatley, D. I. Burton, I. Mouret, M. Allenspach, J. Brews, R. Schrimpf, K. Galloway & R. L. Pease, "Impact of Oxide Thickness on SEGR Failure in Vertical Power MOSFETs; Development of a Semi-Empirical Expression," ibid, NS-42, No. 6, 1928 (Dec., 1995)

(7) A. E. Waskiewicz & J. W. Groninger, "Burnout Thresholds and Cross Sections of Power MOS Transistors with Heavy Ions " Rockwell International Rept No. DNA-MIPR-88-507 (Feb., 1990).

(8) G. H. Johnson, R. D. Schrimpf, K. F. Galloway, R. Koga, "Temperature Dependence of Single-Event Burnout in N-Channel Power MOSFETs," *IEEE Trans. on Nuclear Science*, NS-39, No. 6, 1605 (Dec., 1992).

(9) J. H. Hohl & G. H. Johnson, "Features of the Triggering Mechanism for SEB of Power MOSFETs," *IEEE Trans. on Nuclear Science*, NS-36, No. 6, 2260 (Dec., 1989)

(10) J. H. Hohl & K. F. Galloway, "Analytical Model for SEB of Power MOSFETs," *IEEE Trans. on Nuclear Science*, NS-34, No. 6, 1275, (Dec., 1987)

(11) T. F. Wrobel & D. E. Beutler, "Solutions to Heavy Ion Induced Avalanche Burnout in Power Devices," *IEEE Trans. on Nuclear Science*, NS-39, No. 6, 1636 (Dec., 1992)

(12) S. Kuboyama, S. Matsuda, M. Nakajima, T. Kanno, T. Ishii, "Numerical Analysis of SEB of Power MOSFETs," *IEEE Trans. on Nuclear Science*, NS-40, No. 6, 1872 (Dec., 1993)

(13) J. Brews, M. Allenspach, R. Schrimpf, K. Galloway, J. Titus, C. Frank Wheatley, "A Conceptual Model of SEGR in Power MOSFETs," *IEEE Trans. on Nuclear Science*, NS-40, No. 6, 1959 (Dec., 1993)

Table 1. The Failure (or Pass/Fail) Vds Voltages for MOSFETs for Indicated Ion Beams

NOTE: The * appearing in Column 1 indicates new or revised data. Contiguous row entries are repeated data shown here to put new data in context. This table is not an accumulation of all prior test data reported in 1994.

Mfr	Mfr Number	Generic No	Channel	Sample	BVds	Vgs(off)	Low Z Ions	Fe,Ni,Co, LET=27	Br or Kr, LET=	High Z Ions	High Energy Ions	Failure	Test Org	Date	Location	Remarks
*MOT	IRF440		n	3	500	30V			240(196 MeV Br)			SEGR	UA	*1994	IPN	Mouret, IEEE94. Room T. Angle data exist
*PHIL	ECG2392		n	1	100	0					60 (LET=44)	SEGR/SEB	J	*11/95	TAM	Nichols. 1961 MeV Xe
*Ixys	IXFM40N25RH		n	6	250	0	200(Ne),140(Ar)		55(Kr)			SEB	J	*3 & 6/90	88	Nichols, Higher threshold at 100 deg. C.
*Ixys	IXTM35N30		n	4	300	0	225(Ne),160(Ar)		67(Kr)			SEB	J	*6/90	88	Nichols, Higher threshold at 100 deg. C.
*Ixys	IXTM21N45		n	5	450	0	316(Ne),214(Ar)		144(Kr)			SEB	J	*3 & 6/90	88	Nichols, Higher threshold at 100 deg. C.
*Ixys	IXFM21N45RH		n	3	450	0	300(Ne),270(Ar)		140(Kr)			SEB	J	*3 & 6/90	88	Nichols, Higher threshold at 100 deg. C.
*SIL	VN88AF		n	1	80	0V					60/70 (LET=44)	SEB	J	*11/95	TAM	Nichols. 1961 MeV Xe
*SIL	VN88AF		n	1	80	10V					60/65 (LET=44)	SEB	J	*11/95	TAM	Nichols. 1961 MeV Xe
SIL	IRFF130	2N6796	n	2	100	10V	100(N),100(Ne),70(Ar),	50(Cu)				SEB	R/A	*1990	88"	Compare to INR device (1994 compendium)
*SIL	IRFF130	2N6796	n		100	5V		50(Co)				SEB	B	*7/95	88"	Oberg. Ambient & 100 deg. C.
*SIL	9230 family	2N6851	p		200	5		Hard(Co)				N/A	B	7/95*	88	Oberg. -100 deg C. (looking for SEGR)
*SIL	420 family	2N6794	n		500	5		300 (Co)				SEB	B	*3/95	88	Oberg. Ambient & 100 deg. C.
*SIL	430 family	2N6802	n	10(lot)	500	5		317 (Co)				SEB	B	*7/95	88	Oberg. Ambient & -100 deg C.
SIL	430 family	2N6802	n		500	5		300				SEB	B	*4/93	88	Ambient=45 deg. C.
	(continued)					12		300				SEB/SEGR	B	*10/93	UW	Temp=100 deg. C.
*SIL	VP0610 -low power		p	7	60	25V		Hard(Ni)				N/A	HSS	*4/95	BNL	Lintz-Room T.
*SIL	VP0610 -low power		p	7	60	25V		Hard(Ni)				N/A	HSS	*4/95	BNL	Lintz-120 deg. C.
*INR	IRHM7054		n	4	60	12V			55(Br)	<35(I)		SEGR	C	*4/95	BNL	Titus. Rept #SEGR-003 25 deg. C. only
	continued					20V			46(Br)			SEGR	C	*4/95	BNL	Titus. Rept #SEGR-003 25 deg. C. only
INR	IRHM7054		n		60	0V		Hard(Ni)				N/A	R	*7/93	BNL	DC9242 Bob Ferndon 7/13/93
	continued					5V		Hard(Ni)				N/A	R	*7/93	BNL	DC9242 Bob Ferndon 7/13/93
*INR	IRF140	2N7218	n		100	0 & 5		85/90(Ni)				SEB	BNL	*6/93	BNL	9310, Lintz. Same response at Room T & 90 deg. C.
INR	IRF140		n		100	0		Hard(Ni)	70/80(Br)			SEB	ESA	*1/94	BNL	9203E, Harwell Rept AEA-RS-1348
*INR	IRF150	2N6764	n		100	0, 1 & 5		85/90(Ni)				SEB	HSS	*6/93	BNL	9232, Lintz. Same response at Room T & 90 deg. C.
INR	IRF150	2N6764	n		100	0		90/100(Ni)	70/80(Br)			SEB	ESA	*1/94	BNL	9229G, Harwell Rept AEA-RS-1348
INR	IRF150	2N6764	n	3	100	10	100(Ne),70(Ar)	50(Cu)			40/60(12 GeV La-Bev.)	SEB	R/A & J	1990	88	JPL: Bevalac ion LET=30, 6/88.
INR	IRF150	2N6764	n		100	0	105	75	75			SEB	A	*5/92	88	Koga
INR	IRF150	2N6764	n	3 each	100	off	100(208 MeV Cl)	70(Ni)	65(Br)	55(I)	50(1 to 4 GeV Xe) GANIL	SEB	CNES	11/90	BNL	3 GANIL ions. Tastet, RADECS91
INR	IRF150	2N6764	n		100	0	100(208 MeV Cl)	>80(Fe)			80/100(>1 GeV Fe)(1)	SEB.	J	6/88	BNL	(1)Two Fe ions at Bevalac, each LET<6.
INR	IRH150		n		100	0		100(Fe) 100(Cu)	100(Kr)		60/100(12GeV La)(1)	SEB	J & R	1990	88	(1)=JPL at Bevalac. June,1988
	continued		n		100	10		100(Cu)	90/100(Kr)			?	R	1990	88	Waskiewicz & Groninger, DNA Rept. 2/90
*INR	IRHF7110		n	4	100	12V			85(Br)	41(I)		SEGR	C	*4/95	BNL	Titus. Rept #SEGR-003. 25 deg. C. only.
	continued					20V			63(Br)	29(I)		SEGR	C	*4/95	BNL	Titus. Rept #SEGR-003. 25 deg. C. only.
INR	IRHF7110		n		100	2V		Hard(Ni)	Hard(Br)			N/A	R	*7/92	BNL	90 deg. C.
	continued					15V		Hard(Ni)	70(Br)			SEGR	R	*7/92	BNL	90 deg. C.
*INR	IRF250	2N6766	n		200	0,1 &5		135/140(Ni)				SEB	HSS	*6/93	BNL	9239, Lintz. Same response at Room T & 90 deg C.
INR	IRF250	2N6766	n		200	0		120/140(Ni)	<120(Br)			SEB	ESA	*1/94	BNL	9229G, Harwell Rept AEA-RS-1348
INR	IRF250	2N6766	n		200	0		*150	*135			SEB	A	*9/89	88	Koga
INR	IRF250	2N6766	n		200	0?		140(Fe),120(Cu)	100(Kr)		80(Two La ions)	SEB	A & B	1988	88/Bev	Oberg & Kolasinski. Bev=Bevalac(now defunct.)
	continued			2		10	200(Ne),120(Ar)	90(Cu),100(Ni)	85(Br)			SEB	R/A	1990/1992.	88/BNL	Waskiewicz
	continued			3 each		off	200(Cl)	135(Ni)	112(Br)	107(I)	100(Xe)-GANIL	SEB	CNES	11/90	BNL	3 GANIL ions. Tastet, RADECS91
INR	IRF250		n	5	200	off			165 (212 MeV Br)			SEB	CNES	*9/93		2 GANIL ions also. Tastet, RADECS93. p 452.
INR	IRF250	2N7225	n		200	5		150				SEB	B	11/93	88	Temp= 25 deg. C.
	continued					5		160				SEB	B	11/93	88	Temp= 100 deg. C.
INR	IRFM250	2N7225	n	2	200	5			130(Kr)			SEB	NASDA	2&3/95	JAERI?	Shinosaki. 80 deg. C. LDC9120. NEED ROOM TEMP

Mfr	Mfr Number	Generic No	Channel	Sample	BVds	Vgs(off)	Low Z Ions	Fe,Ni,Co, LET=27	Br or Kr, LET=	High Z Ions	High Energy Ions	Failure	Test Org	Date	Location	Remarks
*INR	IR7250		n	18	200	2V			125(Br)	50(Au)		SEGR	C	*8/95	BNL	Titus
	continued					15V			75(Br)	25(Au)		SEGR	C	*8/95	BNL	Titus
*INR	IRH9250		p	6	200					80/90 (Xe)		SEGR	A		88	Koga. No SEB with Kr at Vds=200
*INR	IRF310	2N6786	n		400	0 & 5		250/270(Ni)				SEB	HSS	*11/93	BNL	9310. Lintz. Room T
*INR	IRF310	2N6786	n		400	0 & 5		270/290(Ni)				SEB	HSS	*11/93	BNL	9310. Lintz. 90 deg. C.
NR	IRF310	2N6786	n		400	0		260/270(Ni)	250/260(Br)			SEB	ESA	*1/94	BNL	9228G, Harwell Rept AEA-RS-1348
*INR	IRF330	2N6760	n	5	400	0		245/250(Ni)				?	HSS	*4/95	BNL	DC9447, Room T. Lintz
*INR	IRF330	2N6760	n	4	400	0		280/285(Ni)					HSS	*4/95	BNL	DC9447, 90-150 deg. C. Lintz
*INR	IRF330	2N6760	n	3	400	switched		Hard (Ni)				N/A	HSS	*4/95	BNL	DC9447,125 KHz, 0/10V,40% duty "off". Lintz
NR	IRF330	2N6800	n		400	0V		240/260(Ni)	200/240(Br)			SEB	ESA	*1/94	BNL	9228G, Harwell Rept AEA-RS-1348
NR	IRFF330	2N6800	n		400	2V		<235 (Cu)	235(Br)			SEB	R	*7/92	BNL	90 deg. C.
	continued					15V			235(Br)			SEB	R	*7/92	BNL	90 deg. C.
NR	IRFF330	2N6800	n		400	5V		240(LET=28)				SEB	B	*12/92	UW	100 deg. C. [illegible]
*INR	IRFF330	2N6800	n		400	5V		240(Co)				SEB	B	*3/95	88	Oberg. Room T & 100 deg. C tests.
*INR	IRF340	2N7221	n	5	400	0		255/260(Ni)				[illegible]	HON	*4/95	BNL	DC9307, Room T. Lintz
*INR	IRF340	2N7221	n	5	400	0		285/290(Ni)				[illegible]	HON	*4/95	BNL	DC9307, 90-120 deg. C. Lintz
*INR	IRF340	2N7221	n	5	400	switched		Hard(Ni)				SEB	HON	*4/95	BNL	DC9307,200 KHz, 0/10V,50% duty cycle. Lintz
NR	IRF340		n		400	0		250/260(Ni)	240/280(Br)			SEB	ESA	*1/94	BNL	9228G, Harwell Rept AEA-RS-1348
NR	IRF340		n		400	2		245				SEB	MWA	*8/93	BNL?	DC:8924,9031,9110. Dr. T. Rao-Sahib
NR	IRF340		n		400	5		260				SEB	B	*5/94	88in	Oberg. 45 & 100 deg. C.
*INR	IRF350	2N6768	n	5	400	0V		[illegible]				SEB	HSS	*4/95	BNL	DC9501, Room T. Lin
*INR	IRF350	2N6768	n	3	400	0V		280/285(Ni)				SEB	HSS	*4/95	BNL	DC9501, 90-120 deg. C. Lintz
*INR	IRF350	2N6768	n	5	400	switched		350/360(Ni)				SEB	HSS	*4/95	BNL	DC9501,200 KHz, 0/10V,40% duty "off". Lintz
NR	IRF350	2N6768	n		400	?					130(LET=32)	SEB	CNES	*1992	GANIL	Dufour et al., 92IEEE Workshop
NR	IRF350	2N6768	n		400	5V		*260				SEB	B	*6/93	88in	Oberg. Vth=280 at 100 deg. C.
*INR	IRF350	2N6768	n		400	5V		240 (Pass)(Co)				SEB	B	*5/94	88in	Oberg. Room T & 100 deg. C tests.
NR	IRF350	2N6768	n		400	0V		260/280(Ni)	200/240(Br)			SEB	ESA	*1/94	BNL	9228G, Harwell Rept AEA-RS-1348
*INR	IRF360		n	4	400	12		[illegible]				SEB	HSS	2/93	BNL	DC9238G. Lintz (revised entry for 1994)
*INR	continued			2		switched		250/300(Ni)				SEB				9238. Lintz +12 & -12V. (revised for 1994)
NR	IRF360		n	5&4	400	0		220/230(Ni)	225/250(Br)			SEB	R	9 &12/92	BNL	DC9143. Br 90 deg. C.; Ni @ room T.
	continued			5&1		5		220/250(Ni)	225/250(Br)			SEB				
NR	IRF420	2N6794	n		500	5		300 at high T				SEB	B	11/93	88	Oberg. 100 deg C. ROOM TEMP DATA = worst case.
*INR	IRF420		n	9	500	switched		340/380(Ni)				SEB	HSS	*8/95	BNL	DC9517. Lintz. 125 KHz, 0 to 10V. Off=3.2us.
NR	IRF430	2N6802	n		500	0		300/350(Ni)	320(Br)			SEB	ESA	*1/94	BNL	9228G, Harwell Rept AEA-RS-1348
NR	IRF430	2N6762	n		500	?			<310(Cu)			[illegible]	R	1990	88	
*INR	IRFF430		n	2	500	0		305/310(Ni)				[illegible]	[illegible]	*8/94	BNL	Lintz. Also survived 450V Vds peak at 37KHz.
NR	IRFF430	2N6802	n		500	?				500(Au)			JH		BNL	Au has inadequate range =27 mic.
NR	IRFF430	2N6802	n		500	?				275(LET=100)		SEB	JH		BNL	J. Kinnison
*INR	IRFF430	2N6802	n	10(lot)	500	5		316 (Co)				SEB	B	7/95	88	Oberg. ambient & High T (~100 deg C)
NR	IRFF430	2N6802	n		500	5		300				SEB	B	*4/93	88	Oberg. ambient = 45 deg. C.
	(continued)					12		325				SEB	B	*10/93	UW	Oberg. Temp=100 deg. C.
NR	IRF440		n		500	0		300/350(Ni)	250/300(Br)			SEB	ESA	*1/94	BNL	9228G, Harwell Rept AEA-RS-1348
NR	IRF440		n		500	5		300				SEB	B	6/93	88	Oberg. ambient = 45 deg. C.
NR	IRF440		n		500	12		325				SEB	B	6/93	88	Oberg. Temp =100 deg. C.
*INR	IRF440		n		500	12		300 (Co)				SEB	B	5/94	88	Oberg. Ambient &100 deg. C.
*INR	IRF440		n	4	500	20			220(196 MeV Br)			SEGR	UA	*1994	IPN	Mouret, IEEE94. Room Temp. Angle data exist.
NR	IRF450	2N6770	n		500	0		300/350(Ni)	300 (Br)			SEB	ESA	*1/94	BNL	9228G, Harwell Rept AEA-RS-1348
NR	IRF450	2N6770	n	5 &1	500	0		290/300(Ni)	275/300(Br)			SEB	R	9 & 12/92	BNL	Br @ 90 deg. C.; Ni @ room T.
	continued			5 &3		5		290/300(Ni)	275/300(Br)			SEB	R	9 & 12/92	BNL	Br @ 90 deg. C.; Ni @ room T.
NR	IRF450	2N6770	n		500	?					250(LET=23)	SEB	CNES	1992	GANIL	Dufour et al., 92IEEE Workshop
*INR	IRF450	2N6770	n	4	500	switched						SEB	HSS	*8/95	BNL	DC'93. Lintz, 62.5 KHz. "Off"=5.9 us.
*INR	IRFM450		n	~25	500		360(Ne), 330(Ar)	300(Cu)	300(Kr)			SEB	A	*4/95	88	Koga. SEB cross section vs LET for Ne,Ar,Cu,Kr.
NR	IRH450		n	2/4 ea.	500	off			350(Br)	325(I)	250(Xe)-GANIL	SEB	CNES	11/90	BNL	3 GANIL ions, Tastet, RADECS91

Mfr	Mfr Number	Generic No	Channel	Sample	BVds	Vgs(off)	Low Z Ions	Fe,Ni,Co, LET=27	Br or Kr, LET=	High Z Ions	High Energy Ions	Failure	Test Org	Date	Location	Remarks
*INR	IR7450		n	18	500	0			385(Br)	160(Au)		SEGR	C	8/95	BNL	Titus Rept. "SEGR-002. 25 deg C. only
	continued					15			400(Br)	100(Au)		SEGR	C	8/95	BNL	Titus Rept. "SEGR-002. 25 deg C. only
INR	IRH7450		n		500	?			310 (Br)			SEB	CNES	1990	?	
INR	IRH7450	2N6770	n	5&5	500	0 to 2		300/325(Ni)	250/275(Br)	<120(!)		SEGR	R & C	7/9/12/92	BNL	R:90 deg. C. Epi=40-50 mic. for high V parts.
	continued			5&4		5		275/300(Ni)	225/250(Br)			SEGR	R	9 &12/92	BNL	90 deg. C
	continued					15		No data	155(Br)			SEGR	R	7/92	BNL	90 deg. C.
INR	IRHM7450		n		500	5		300				SEGR	B	1/93	UW	Oberg. Temp=100 deg. C.
*INR	IRH7450SE		n	10	500	5		373/400(Co)				SEB	B	7/95	88	Oberg. Ambient and -100 deg. C.
*INR	IRH7450SE		n	23+	500		>>400(Ne), 360(Ar)	350(Cu)	350(Kr)			SEB	A	4/96	88	Koga. SEGR Vds(threshold) vs Vgs data exist for Kr.
*HAR		2N6782	n	13	100	0 & 5		40/45(Ni)				SEB	HSS	11/93	BNL	9252. Lintz. Same response at room T & 90 deg. C.
*HAR	IRF140		n	5	100	25			50(196 MeV Br)			SEGR	UA	1994	IPN	Mouret, IEEE94. Room temp. Angle data exist.
HAR	FRM140D1	2N7283	n	2	100	0			70/80(Br)			SEGR	J	91/92	BNL	Data @100 deg C exists for Vgs=0 & 15.
	continued			3*		15			20/40(Kr)			SEGR	J	91/92	88-in	HAR says these are not latest technology.
HAR	FRM140	2N7283	n		100	5		99				?	HAR	"1993"	BNL?	Space Station Freedom (SSF) Table
*HAR	IRF150	2N6764	n	2	100	0					40/50 (1960 MeV Xe)	SEB	J	11/95	TAM	Nichols. LET(Xe)=44.
*HAR		2N6764	n	1	100	10					45/50 (1960 MeV Xe)	SEGR	J	11/95	TAM	Nichols. Note change in failure mode vs Vgs.
*HAR	FSF150R		n		100	<20			Hard(Br)	Hard(!) for Vgs=0 only.		SEGR	C	"1995"	BNL	Titus, IEEE95. FSF= "SEE Hard"
HAR	FRK150R	2N7291	n	5	100	0		80/100(Ni)				SEGR	R	12/92	BNL	90 deg. C
	continued			4		5		80/100(Ni)				SEGR	R	12/92	BNL	90 deg. C
HAR	FRK150	2N7291	n		100	5		97				?	HAR	"1993"	BNL?	Space Station Freedom (SSF) Table
*HAR	FRF9250		p	4	200					160/180 (Xe)		SEGR	A		88	Koga. No SEB at LET=40 for Vds=200.
HAR	FRM9250		p	3	200	0		Hard @ 200(Ni)				N/A	J	12/93	BNL	1 of 3 older version failed at Vds=200/Vgs=0.
	continued			3		15		Hard @ 200(Ni)				N/A	J	12/93	BNL	Older version not tested at Vds=15.
HAR	FRL234R		n	5	250	0		175/200(Ni)				SEGR	R	3/93	BNL	90 deg. C. DC:9312
HAR	FRM234		n		250	5		238(Pass)				?	HAR	"1993"	BNL?	Space Station Freedom (SSF) Table
*HAR	FSL234		n		250	5		250 Hard (Co)				N/A	B	3/95	88in	Oberg
*HAR	TA17663		n	6	250	0	250(Ne),250(Ar)		245(Kr)			SEB	J	3 & 6/90	88	Nichols. Hard at 100 deg. C
*HAR	FSF254R		n		250	0			Hard(Br)	170(!)		SEGR	C	"1995"	BNL	Titus, IEEE95, see p 1933. FSF="SEE-Hard".
*HAR	FSF254R		n		250	15						SEGR	C	"1995"	BNL	Titus, IEEE95, see p 1933. FSF="SEE-Hard".
HAR	FRF254R	2N7296	n	2	250	5			100(Kr)			SEGR	NASDA	2&3/95	JAERI?	R. Shinozaki. 80 deg. C. LDC9041
*HAR	FSL254		n		250	5		250 Hard (Co)					B	3/95	88	Oberg
*HAR	TA17463RH	develop'tl	n	6	275	0	210(Ne),175(Ar)		75(Kr)			SEB	J	3 & 6/90	88	Nichols. Higher thresholds at 100 deg. C
*HAR	FRL430D		n	4	500	0		>400(Ni)	<250(Br)			SEGR	HSS	12/93	BNL	DC9138. Lintz. 'Revised'
*HAR	IRF440		n	5	500	15			246(196 MeV Br)			SEGR	UA	1994	IPN	Mouret. IEEE94. Room T. Angle data exist.
*HAR	TA17465		n	2	500	0	410(N), 380(Ne)		250(Kr)			SEB	J	3 & 6/90	88	Nichols, room T
*HAR	TA17665RH		n	6	500	0			494(Kr)**			SEB	J	3 & 6/90	88	Nichols, room T. One of the six failed @ 323V (Kr).

Addendum-- Harris Space Product News (3rd Quarter, 1994) reports collective data for FS series-- A SEGR hard version of their FR series. Harris claims that all three transistor types (BV=100, 250, 500) uniformly survive SEGR with energetic particles of LET=36 MeV/mg/cm2 at 80% of rated drain source breakdown and an off gate bias of 10 volts. BNL tests of 7/93 & 4/94.

Manufacturers: HAR= Harris, INR=International Rectifier, Ixys= Ixys Corp., MOT=Motorola, PHL=Phillips, SIL=Siliconix.

Testers: A=Aerospace (R. Koga & W. Crain), B= Boeing (D. Oberg, J. L. Wert, W. Will), C=Crane NWSC (J. Titus), CNES=Centre National D'Etudes Spatiales, ESA= European Space Agency (L. Adams), HAR= Harris, HON= Honeywell (J. Pollock, Houston, 713-293-1934), HSS= Honeywell Space Systems (J. Lintz), J= JPL (D. Nichols 818-354-5787, T. Miyahira), JH= John Hopkins APL (J. Kinnison), R=Rockwell (A. Waskiewicz), S=Sandia (T. Fischer), MMA= Martin Marietta Astrospace (James Coleman, Valley Forge,PA).
UA= Univ. Arizona (Brews, Galloway et al.)

Facilities: 88= 88-in cyclotron (Berkeley), Bev= Berkeley Bevalac, BNL= Brookhaven Natl Lab Van de Graaff, GANIL=French National High Energy cyclotron, UW= U. of Wash. Van de G. (low & medium energy modes)
IPN=Institut de Physique Nucleaire, Van de Graaff, Orsay, France (low energy), NASDA= National Space Development Administration (Japan) heavy ion accelerator, TAM=Texas A&M medium-energy cyclotron