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THE RESPONSE OF SOME AVALANCHE PHOTODIODES TO FAST NEUTRON IRRADIATION

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Using the fast neutron flux available from the beam collector on the RAL spallation neutron source (ISIS) we have irradiated two types of avalanche photodiodes (APD) {Hamamatsu S5345 (high capacitance) and the EG&G C30626E} up to a maximum fluence of 2×10^{13} neutrons per cm^2. We report the behaviour of the device dark currents and noise characteristics through the course of the exposure to the neutron flux.

1. INTRODUCTION

A considerable program of work is in hand in a number of centres aimed at proving the viability of the APD as a scintillation light detector for the electromagnetic calorimeter (ECAL) on the CMS experiment at LHC. Some of this work has been summarised in reference [1]. One important requirement (among many others) is that the devices exhibit a useful electronic dynamic range of 10^5, which in turn demands a low electronic noise threshold. Measurements have shown [2] that with the best devices RMS noise figures (referred to the input) of 50 electrons or less can be achieved at room temperature. APDs are, however, very sensitive to dark current-induced shot noise since the avalanche process amplifies any dark current present in the silicon of the conversion region just as if it were signal. The fast neutron flux generated by the ECAL is expected to be of the order of $2\times10^{12}/\mathrm{cm}^2$/annum. Such levels of flux are known to cause increased dark current in silicon due to the creation of shallow traps which ionise readily at room temperature. Measurements made using a reactor facility at Saclay indicated a serious degradation of the noise performance of both types of APD in fluences comparable to one years running at LHC [1]. We have essentially repeated the measurements using the ISIS facility.

2. THE ISIS FACILITY

At the start of the acceleration cycle of the synchrotron approximately 10% of the injected beam is not trapped by the RF. During the initial phase of the magnet ramp in ISIS this 10% lost beam of 72 MeV protons spirals in and impinges on a cooled graphite block, generating an intense flux of neutrons with an energy spectrum peaking at about 1MeV, falling by a factor of 5 at 0.1MeV and 10MeV. An endless chain is installed in the machine hall which can transport a sample container (60mm long by 50mm diameter) from outside the hall (via a ventillation shaft) to a position approximately 30cm above the collector. When ISIS is running at it's usual beam current (180 - 200μA) samples receive a flux of 10^{12} n/cm^2 in approximately 25 minutes. Calibration of the fluence experienced by the sample is obtained by counting a cobalt foil included with the sample. The neutron spectrum and the calibration procedures are described in detail in reference [3]. A recent calibration of the gamma dose in the test facility showed it to be 17.5kRad per 10^{13}n /cm^2 of neutron fluence.

3. TEST PROCEDURES

In order to operate the APD at a gain of 50 in the ISIS test facility a stand-alone HT unit which could operate viably in the neutron flux was designed. A battery-powered HT supply was produced which could deliver the bias potential required (144V for the S5345 and 284V for the C30626E) with a droop of about 5V after a fluence of 3×10^{12} n/cm^2. This deficit was entirely due to radiation damage affecting the reference junction in the regulator chip used. While this bias deficit had little effect on the gain of the EG&G device, the Hamamatsu APD (with its 16%/V gain vs bias coefficient) gain would drop significantly from the preset value of 50. A large bias resistor (1MΩ) was used to protect the APD from potential breakdown and variations in the dark current during the exposure further reduced the APD gain towards the end of the exposure period. In order to minimise these effects the fluence was fractionated with a maximum step of around 3×10^{12}n/cm^2.

Between each irradiation the devices were measured using the instrumentation developed at RAL for the beam line tests of the ECAL at CERN [2]. The following measurements were made:

1. The total dark current was measured at the nominal M=50 bias voltage. (A voltage monitor was attached to the APD terminal to measure the bias voltage directly.)

For the EG&G devices, the guard ring and the APD currents were monitored separately.

2. The RMS noise at the output of the shaper amplifier (CR-RC = 30ns) was measured on a true RMS voltmeter and calibrated into electrons using a standard test pulse injected into the input of the charge-sensitive preamplifier (10^6 electrons).

3. The output of the basic charge loop of the preamplifier was connected to an Ortec 575 shaping amplifier set with 500ns CR-RC shaping time constants. These pulses were fed to a pulse height analyser in which the full width at half maxima (FWHM) of injected charge test pulses could be measured to quantify the RMS white noise in the system.

4. The gain of the APD was observed by means of an injected light pulse of about 5000 photo-electrons from a blue LED. The amplitude and width of this peak was monitored.

6. A DC measurement of the gain was performed using a constant light flux from a blue LED. The plateau value of the photocurrent at around 30V was taken to represent unity gain and the gain at the nominal bias voltage calculated from the ratio of the photocurrents. As the dark current became large ($>10\mu A$) it was necessary to have a very small protection resistor ($10k\Omega$) to give accurate results. This made the biassing critical with overcurrenting the diode a very real possibility.

The irradiations were carried out at a temperature of about 23C and the diagnostic measurements between 20C and 23C - the temperature was not controlled. The diagnostics were carried out between 1 day and 2 days post irradiation. During a gap in the schedule one of the S5345s was followed from day 2 to day 6 after the last dose (total to date: $4x10^{12}n/cm^2$) without any detectable recovery in the noise.

4. RESULTS

Figure 1 shows the dark current, RMS noise (30ns) and the RMS noise (500ns) as measured for the Hamamatsu S5345 with identifier H048. This APD was maintained biased at a nominal gain of 50 throughout up to a fluence of $2x10^{13}n/cm^2$, i.e. approximately 10 years of LHC operation. (The first set of points on the figure represent the values before irradiation.) The large (300pF) APD capacitance gives a high ($\approx$7000e-) initial noise with 30ns time constants and the (approximately) linearly rising dark current does not start to seriously increase the noise till we reach $\approx 10^{12}n/cm^2$ i.e. about 6 months operation on LHC. With 500ns time constants one is much more susceptible to dark current-induced shot noise and the noise rises immediately. The 30ns noise seems to saturate at about 20000 electrons and the 500ns noise at just over 100000 electrons. The dark current increases approximately linearly throughout the whole exposure, increasing from 250nA to $20\mu A$.

Given the complexities of keeping an APD biased in our facility it seems a good idea to see if the presence of the bias changed the effect of the neutrons on the silicon. Figure 2 shows the same results plotted for sample H049 which was irradiated simultaneously with H048 for part of the schedule with no bias applied to it. As can be observed from figure 2 there appears to be no first order difference over the region tested.

Figure 3 shows the same data plotted for the EG&G APD identified as E135. Here we note the very low initial noise (≈ 1500e-) arising from the low capacity of the device (30pF) and the extremely low dark current (6nA) arising from the guard ring structure. The effects of the neutrons on this device are much more dramatic. After $2\text{x}10^{12}$n/cm^2 the dark current has increased to 2.5μA and the RMS noise (30ns) is identical to that of H048 at ≈ 11000 electrons. From being a negligible contribution the shot noise becomes dominant after just a month or two of LHC running.

It will be noted that the data of figure 3 stop at a fluence of $2\text{x}10^{12}$n/cm^2. This is because irreversible structural change appeared to occur at this point and render continuation valueless. Figure 4a shows the behaviour of the dark currents of E135 observed when the diagnostic tests were made after two fractions of dose. The device was removed from bias in the irradiation facility and transferred immediately (60 seconds) to the test box. The APD current behaved normally but the guard ring current started at a very high value and settled to an equilibrium value (about half of the starting value) in about one hour. At a fluence of $2\text{x}10^{12}$n/cm^2 this equilibrium value had risen to around 40μA (see figure 4b). After resting for several days the guard ring current had settled further to about 30μA and the data point shown on figure 3 was taken. Figure 4c shows the total current and the APD dark current curves measured at this point. E135 was given a further $3\text{x}10^{12}$n/cm^2 without bias applied and on testing it drew no guard ring current indicating a failure of connection internally (the APD did,however, operate normally, if noisily).

At all stages of irradiation the APDs showed the ability to amplify without any obvious problem. However, getting a quantitative check on the gain proved extremely problematical. We have found in the past that for the Hamamatsu devices the DC method of gain determination produced gain data which agreed with that of the manufacturer. In the case of the EG&G device the situation is complicated by the presence of the guard ring. It appears that current flow transfers from one collection zone to the other as the bias alters the internal structure. We found that meaningful values of the gain could only be obtained if the total (i.e. guard ring + APD) current was used. As the irradiations progressed we obtained an enormous range of values (27 to 83) from H048. E135 (over the limited range of dose possible) showed less variation (57 to 75). Thus while being assured that all APDs continue to amplify, we can give no data on the stability of the gain (or more exactly the product of the gain and the quantum efficiency).

5. DISCUSSION

It is interesting to compare our measurements with a simple statistical model of the noise. We assume that the total noise power is the sum of the amplifier noise power (a constant in our context) and the shot noise power:

$$\sigma^2 = \sigma_a^2 + (I_s + I_b M^2 F)1.85\tau/q \qquad \{1\}$$

where σ_a = amplifier noise, τ = CR-RC amplifier shaping time constant, q is the electronic charge, I_s = surface (edge) leakage current, I_b = bulk-generated dark current, M = APD gain, F = excess noise factor.

In the case of a guard ring device such as E135 we can assume that $I_s=0$ and the relation {1} above simplifies to:

$$\sigma = \sqrt{}(\sigma_a^2 + bI_d) \qquad \{2\}$$

where $I_d = MI_b$, and $b = 1.85\tau MF/q = k\tau$

Figure 5 shows the noise of E135 plotted against the measured dark current (APD current only) for the two time constants used. If M and F remain constant then the parameter k should be a constant also. For the 30ns curve k=1597 and for the 500ns curve k=1770 which we can take as reasonable agreement. If we assume that the gain is indeed 50, then we can use the fit parameter to evaluate the excess noise factor. Using the data from the 30ns curve we find that F=2.76, a value consistent with other measurements of these devices.

In the case of the Hamamatsu devices the situation is complicated by the fact that we cannot separate the surface leakage from the bulk leakage. However, if we assume (as is plausible) that the same active centres which contribute to the bulk current also augment the surface currents then it would not be unreasonable to assume that I_s and I_b are proportional to each other. In this case a relation of the form of {2} above should be valid. Figure 6 shows the plot of the noise versus dark current for H048 and H049. Clearly the model works for the S5345 and the data of both samples are consistent with each other. Because of the unknown behaviour of I_s and I_b individually, it is impossible to extract any further information from this plot.

The implication of the fits in figures 5 and 6 is that the simple statistical model works and that the deterioration of the APD noise figures is due to the increase in the dark current caused by the radiation damage. Figure 7 shows the dark current (at M=50) in H048 and E135 as a function of the cumulative neutron fluence. We see that we get reasonable fits of the form:

$$I_d = I_0 + a^*D^b \qquad \{3\}$$

where I_0 is the initial dark current, D is the neutron fluence and a and b are constants. The curves are sublinear with b values of 0.705 for E135 and 0.765 for H048. The overall larger current of H048 is obviously due to the surface component. The assumption of a similar characteristic for I_s and I_d is clearly justified by the closeness of the exponents in the two fits.

Figure 8 compares the dark current curves for H048 and H049. The dark current of H049 is ≈20% higher than that of H048 over the range with a slightly flatter characteristic. Whether this is a significant indication of a difference between the radiation sensitivity of the devices in the biased and unbiased state or simply a reflection of the variability between samples of the device is impossible to say. Since a 20% difference in the dark current generates <10% difference in the noise it may indicate that bias-off irradiations may be reliable for initial tests.

Figure 9 shows the dark current measured at M=1 in H048 as a function of the accumulated fluence. This data fits well to a function of the form of {3} above with an exponent of 0.878, i.e. the response is almost linear. If one assumes that there is negligible edge leakage at a bias of 30V (where this data is taken) then one may believe that this represents the behaviour of the bulk dark current (I_b). If one considers the ratio $I_d(M=50)/I_d(M=1)$ as the dose increases, one finds that it decreases from ≈500 to ≈160 over the range, confirming that the bulk dark current is increasing in significance relative to the surface current.

6. CONCLUSIONS

(i) Noise

It is interesting to compare the results of the ISIS irradiation tests with those of the Ulysse reactor tests. Figure 10 shows the noise data plotted together. The conditions are not sufficiently controlled for a detailed comparison to be made (the time constants and APDs are different) but the main conclusion is clear: whatever one's starting point, at 2×10^{12}n/cm^2 (one year of LHC operation) the RMS noise is of the order of 11000 electrons at 20C and from year one to ten one can expect at least a further doubling of the noise.

The statistical model confirms that the noise is dominated by shot noise from the dark current. This means that cooling the devices will have a beneficial effect. The Saclay results [2] show a reduction of a factor of 3.5 in the 10-year noise figure for the low capacitance S5345 and 2 for the C30626E when run at 0C. It is believed that maintaining the APDs permanently at this temperature would almost eliminate the deterioration completely.

The dominance of shot noise after a few months of LHC running means that there is no scope for increasing the amplifier shaping time constants. The 30ns value chosen for the test beam work is probably optimum for lead tungstate at room temperature.

The structure of the EG&G APD keeps its dark current well below that of H048 yet their noises become comparable in just one year of LHC running. Referring to figures 5 and 6 shows that the parameter b of the fitting equation {2} is 4.79×10^4 for E135 and 1.53×10^4 for H048. Much of the apparent advantage of H048 comes from the fact that a large portion of the dark current is surface (and therefore not amplified); however, it could also be true that H048 has a lower value of the excess noise factor (F).

(ii) Gain Stability

As explained above, our gain measurements proved unreliable and we cannot give any clear guidance on the magnitude of any radiation-induced changes in the intrinsic gain or quantum efficiency of the devices. The implication of our experience points to there being no serious effect. There is, however, a serious practical problem in stabilising the gain to the accuracy demanded by the physics posed by the 2+ orders of magnitude change in the dark current observed at ambient temperature. A significant load resistor is required for the APD for two reasons: to limit the parallel noise contribution and to protect the APD from destructive discharge. A safe level for a discharge current is generally estimated to be ≈ 1mA for devices of this type. This means that for the high capacitance S5345 the load resistor should be at least 150kΩ. In a shot noise dominated situation this value is high enough to contribute little extra noise. Assuming this configuration one can calculate that in the first year of running the gain of H048 biassed with an external reference will decline by 9% due to the 3.6μA increase in the dark current. The prospect of using a local servo to stabilise the APD bias is not made any brighter by our experience that the reference junction of the high quality bipolar regulator chip (LP2952IN) which we used in the HT supply for our tests shifted by ≈4% in the same exposure. APDs with higher operating potentials require higher protection resistors but have lower gain/voltage coefficients and the magnitude of the effect remains similar.

(iii) Damage mechanisms

The Saclay data can be fitted satisfactorily to a conflation of expressions {2} and {3} above. For the two APDs tested one obtains exponents (b) of 0.657 (EG&G) and 0.637 (Hamamatsu). Our corresponding values are 0.705 and 0.765. The closeness of the values tends to hint at a universal mechanism (viz. the generation of lattice damage in the bulk silicon). The difference between the Ulysse and ISIS values probably is significant and probably indicates a difference in the radiation environment.

The similarity of the behaviour of H048 and an unbiased H049 under irradiation leads one to believe that the principal effect of the radiation damage is simply to dope the silicon with shallow donor/acceptor traps. The gain does not seem to be affected and the capacitance is unchanged which implies that the structure is not affected. The devices will be monitored over the next few months but no short term (one week) recovery has been observed so there is no evidence that the effects are strongly dependent on the irradiation dose rate.

(vi) The anomalous behaviour of E135

We have no explanation for the problems encountered by the guard ring structure of E135. The fact that the APD behaved as expected may indicate that it is a packaging problem. This sample was mounted in a stainless steel four lead package.

(v) Operating conditions

Since the present results essentially confirm the findings of the Saclay tests we are driven to the conclusions that: one, as regards response to neutron irradiation it makes little difference which detailed specification of APD one selects if room temperature operation is chosen, the dynamic range will be severely cut down from the proposed 10^5 after a year of LHC running and stable biassing will present a very awkward problem; two, the only real prospect for stable long term operation is to run the APDs at a temperature of around 0C when all the radiation-induced problems would go away.

ACKNOWLEDGEMENTS

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1. Investigation of avalanche photodiodes for EM calorimeter at LHC, A Karar et al, Ecole Polytechnique, IN2P3-CNRS, X-LPNHE/95-10 (Presented at "The First Workshop on Electronics for LHC Experiments", Lisbon, 11-15 September 1995

2. Gain and noise measurements on two avalanche photodiodes proposed for the CMS ECAL, J E Bateman, S R Burge and R Stephenson, RAL-TR-95-001

3. The Radiation Hardness Test Facility, M Edwards and D R Perry, RAL-90-065

FIGURE CAPTIONS

1. The noise and dark current of the Hamamatsu S5345 (high capacitance) APD number H048 (biased to a gain of 50) as a function of fast neutron fluence.

2. The noise and dark current of the Hamamatsu S5345 (high capacitance) APD number H049 (unbiased) as a function of fast neutron fluence.

3. The noise and dark current of the EG&G C30626E APD number E135 as a function of fast neutron fluence.

4a. The time-dependent behaviour of the guard ring current of E135 at two levels of fast neutron fluence.

4b. The total dark current of E135 as a function of the fast neutron fluence to which it had been subjected.

4c. The total dark current and the APD dark current of E135 after exposure to 2×10^{12}n/cm^2 as a function of bias potential.

5. The noise of E135 as a function of dark current for two values of amplifier shaping time constant.

6. The noise of H048 and H049 as a function of dark current for two values of amplifier shaping time constant.

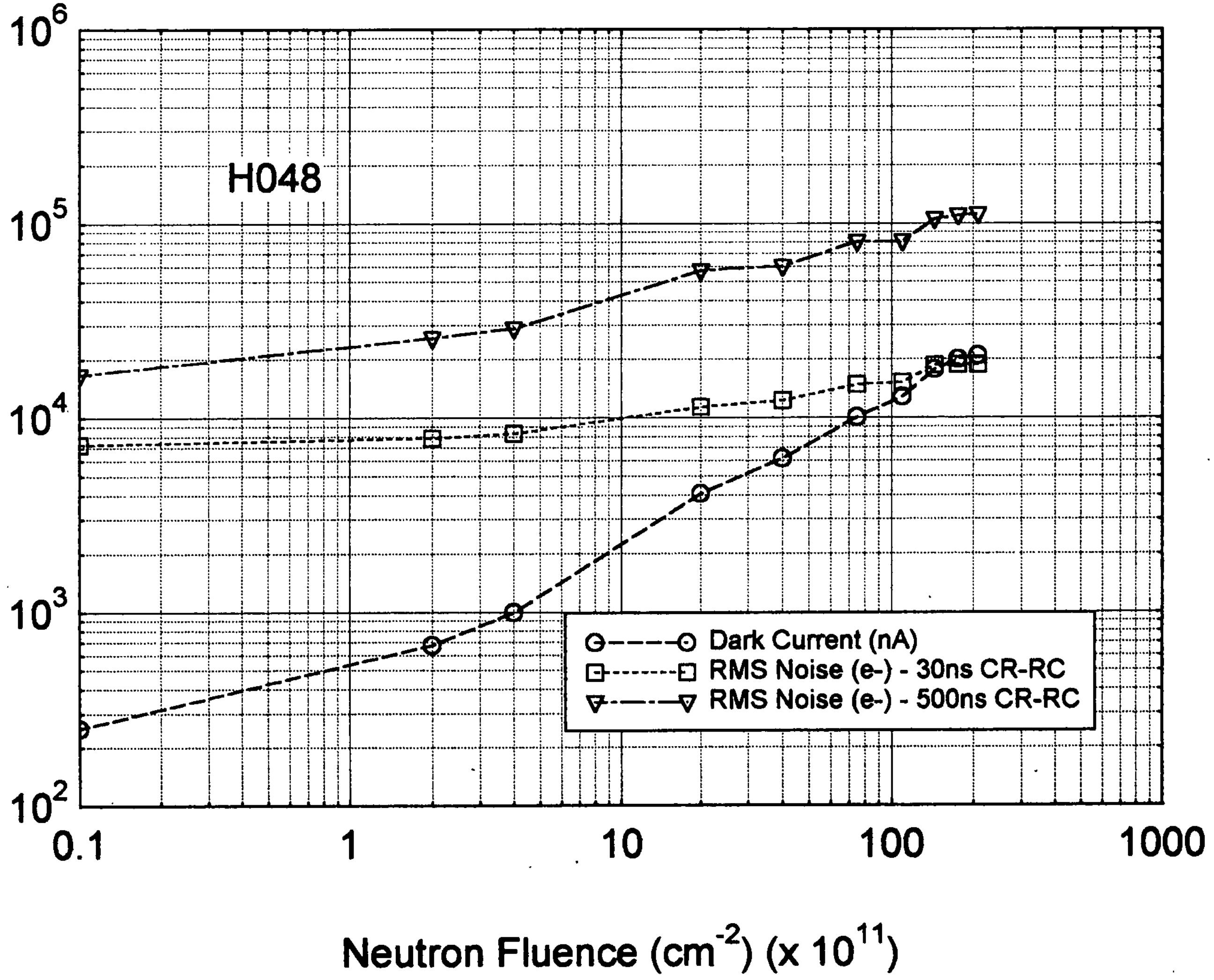
7. The dark current (at M=50) of H048 and E135 as a function of the fast neutron fluence to which they have been subjected.

8. A comparison of the dark currents of H048 and H049 (M=50) as a function of fast neutron fluence.

9. The dark current of H048 as a function of neutron fluence at a bias potential of 30V (M=1).

10. A summary plot showing the present noise measurements (as a function of neutron fluence) and the results obtained in the Saclay tests.

FIGURE 1



H048
10^6
10^5
10^4
10^3
10^2
0.1
1
10
100
1000
Neutron Fluence (cm^{-2}) (x 10^{11})
Dark Current (nA)
RMS Noise (e-) - 30ns CR-RC
RMS Noise (e-) - 500ns CR-RC

FIGURE 2

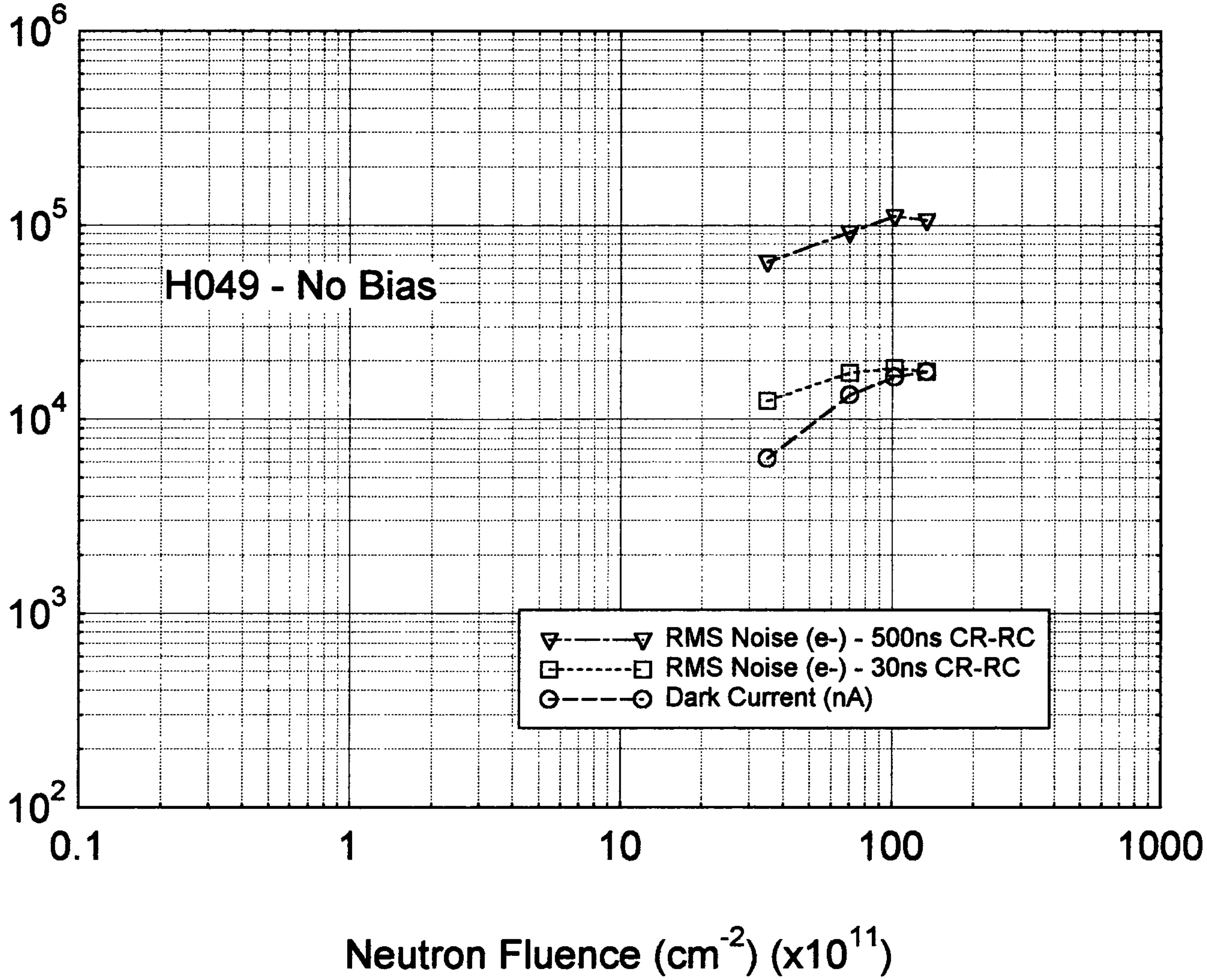
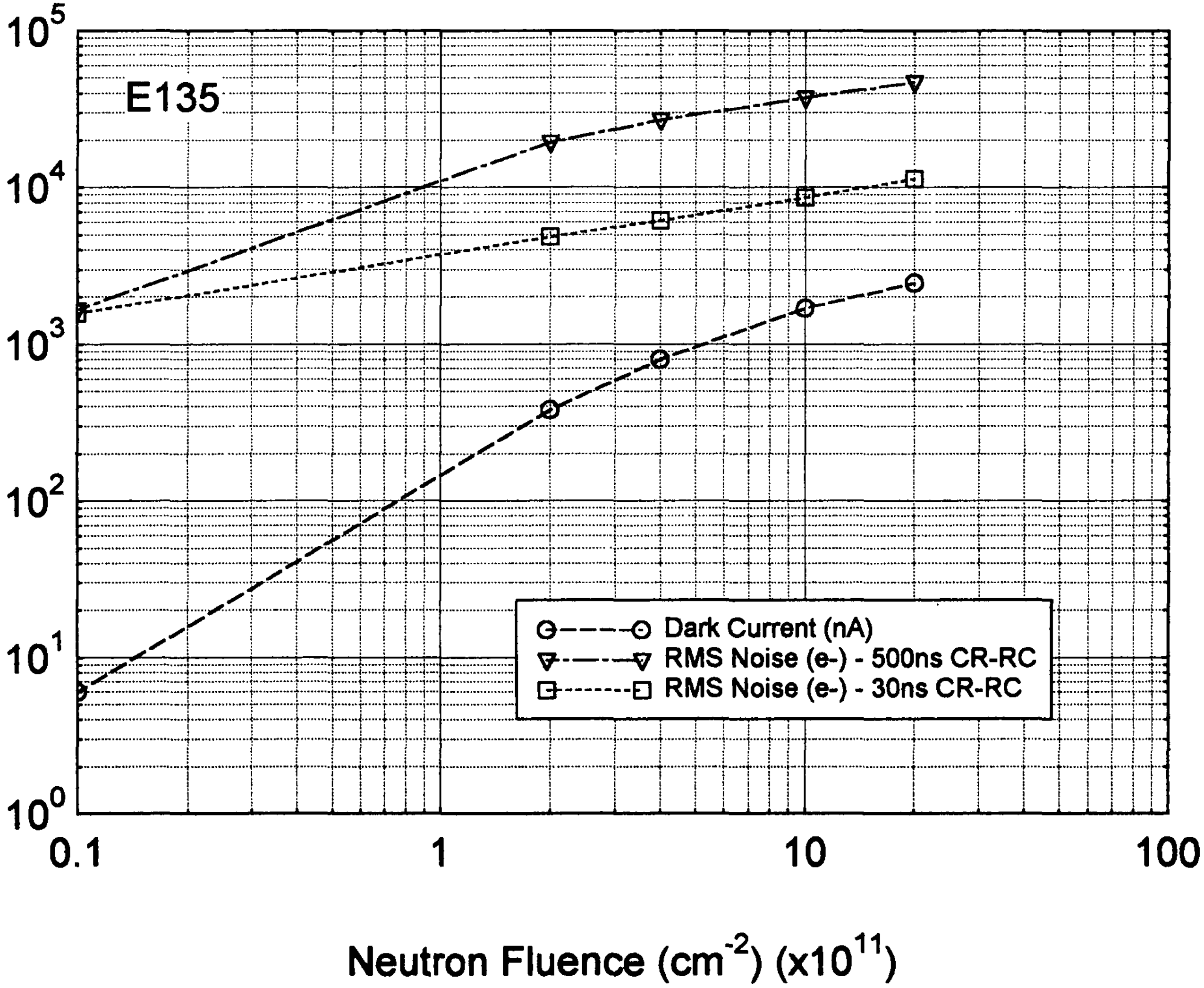

H049 - No Bias
RMS Noise (e-) - 500ns CR-RC
RMS Noise (e-) - 30ns CR-RC
Dark Current (nA)
10^6
10^5
10^4
10^3
10^2
0.1
1
10
100
1000
Neutron Fluence (cm^{-2}) ($x10^{11}$)

FIGURE 3



E135
10^5
10^4
10^3
10^2
10^1
10^0
0.1
1
10
100
Dark Current (nA)
RMS Noise (e-) - 500ns CR-RC
RMS Noise (e-) - 30ns CR-RC
Neutron Fluence (cm^{-2}) ($x10^{11}$)

FIGURE 4a

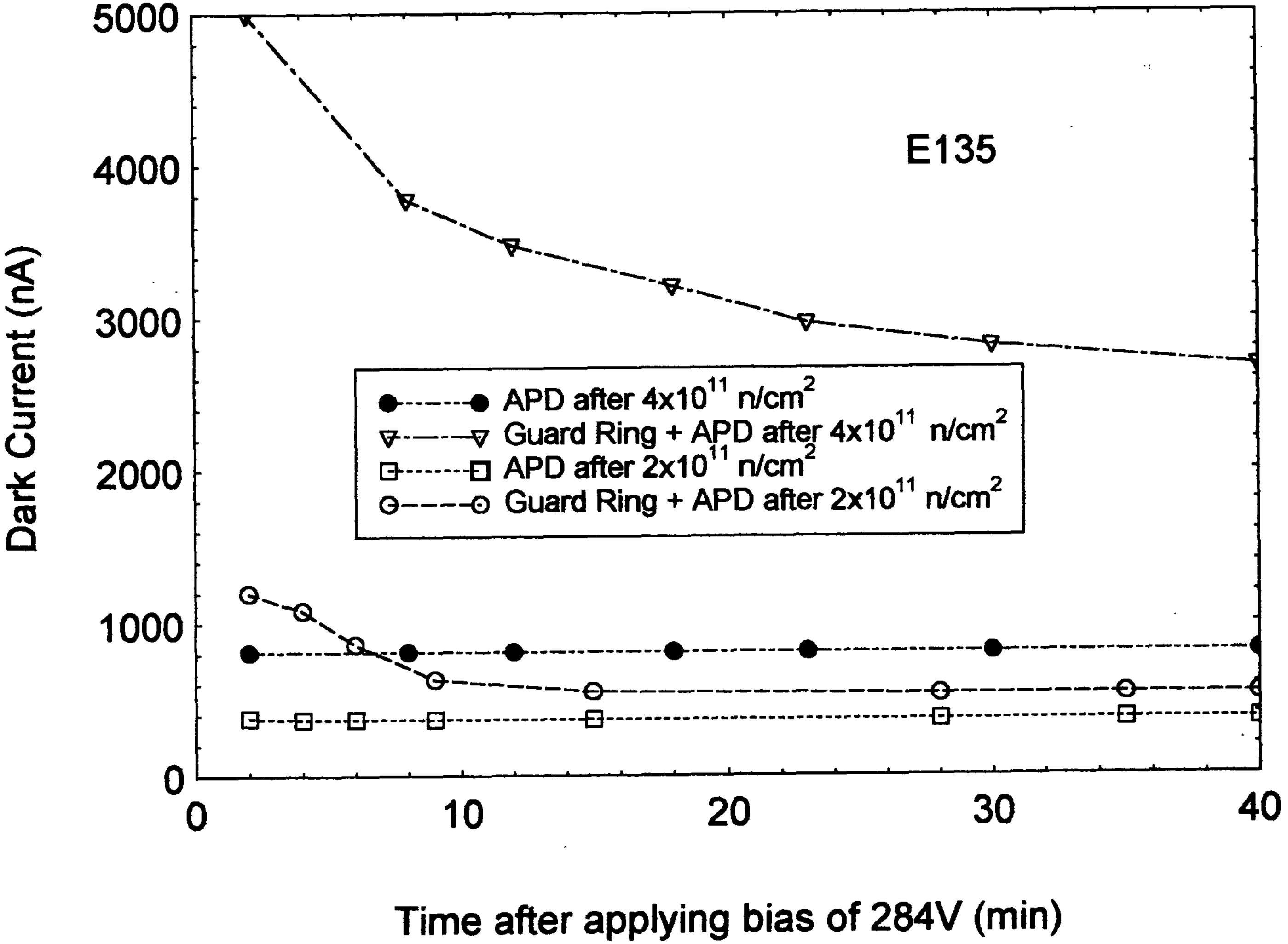

E135
Dark Current (nA)
5000
4000
3000
2000
1000
0
0
10
20
30
40
Time after applying bias of 284V (min)
● APD after $4x10^{11}$ n/cm^2
▽ Guard Ring + APD after $4x10^{11}$ n/cm^2
□ APD after $2x10^{11}$ n/cm^2
○ Guard Ring + APD after $2x10^{11}$ n/cm^2

FIGURE 4b

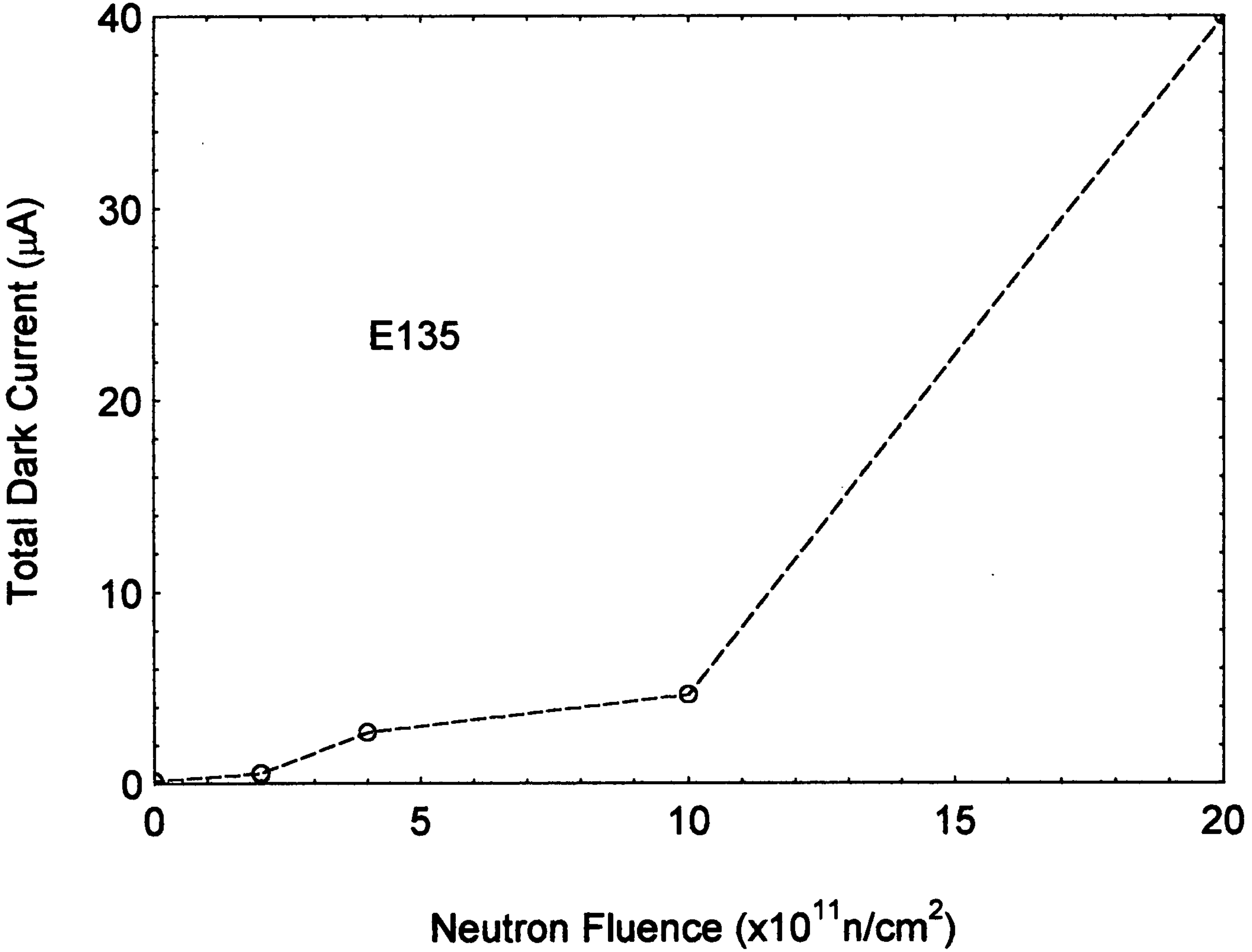
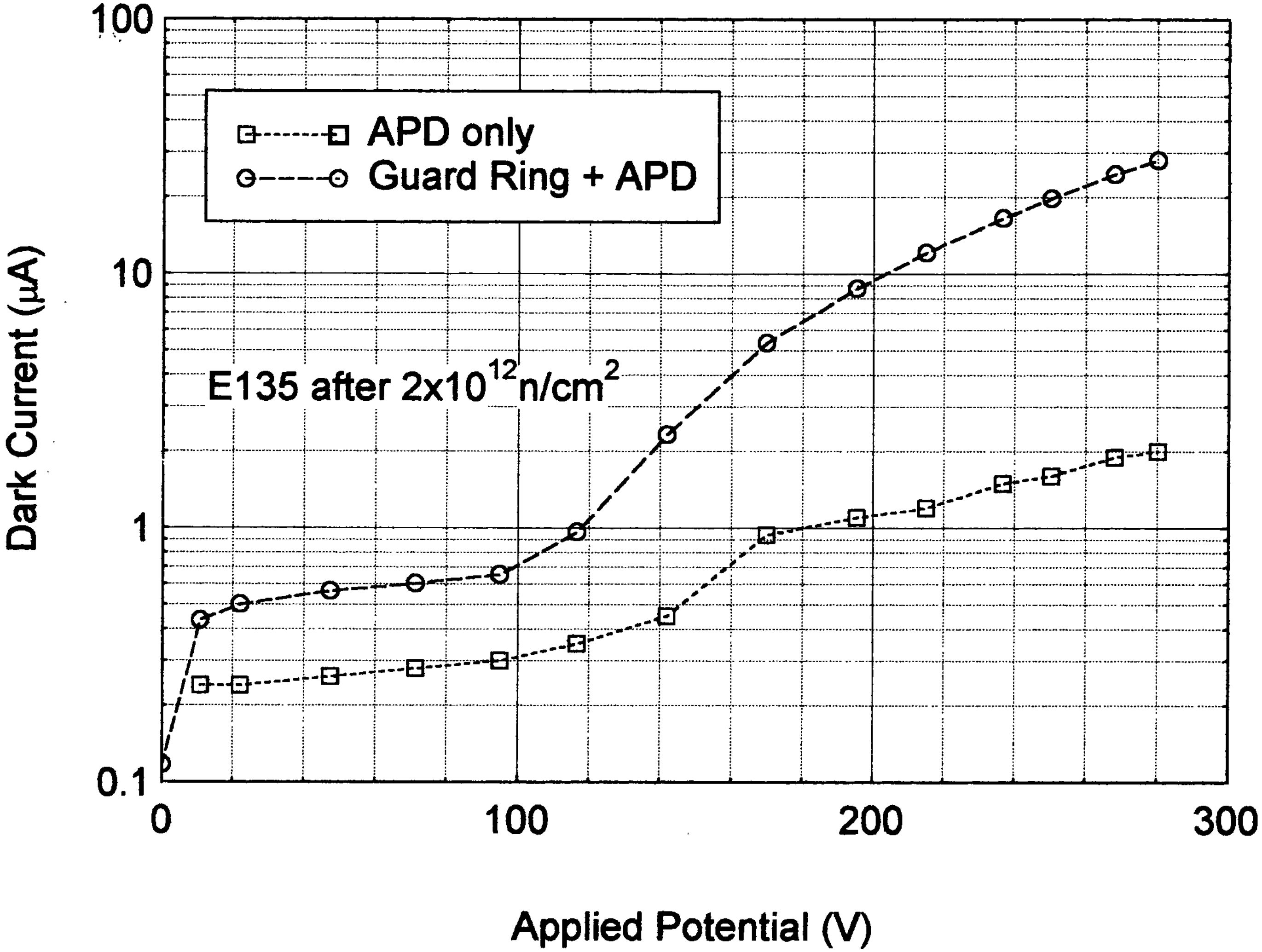

40
30
20
10
0
Total Dark Current (μA)
E135
0
5
10
15
20
Neutron Fluence (x10^11 n/cm^2)

FIGURE 4c



100
10
1
0.1
Dark Current (μA)
APD only
Guard Ring + APD
E135 after 2x10¹²n/cm²
0
100
200
300
Applied Potential (V)

FIGURE 5

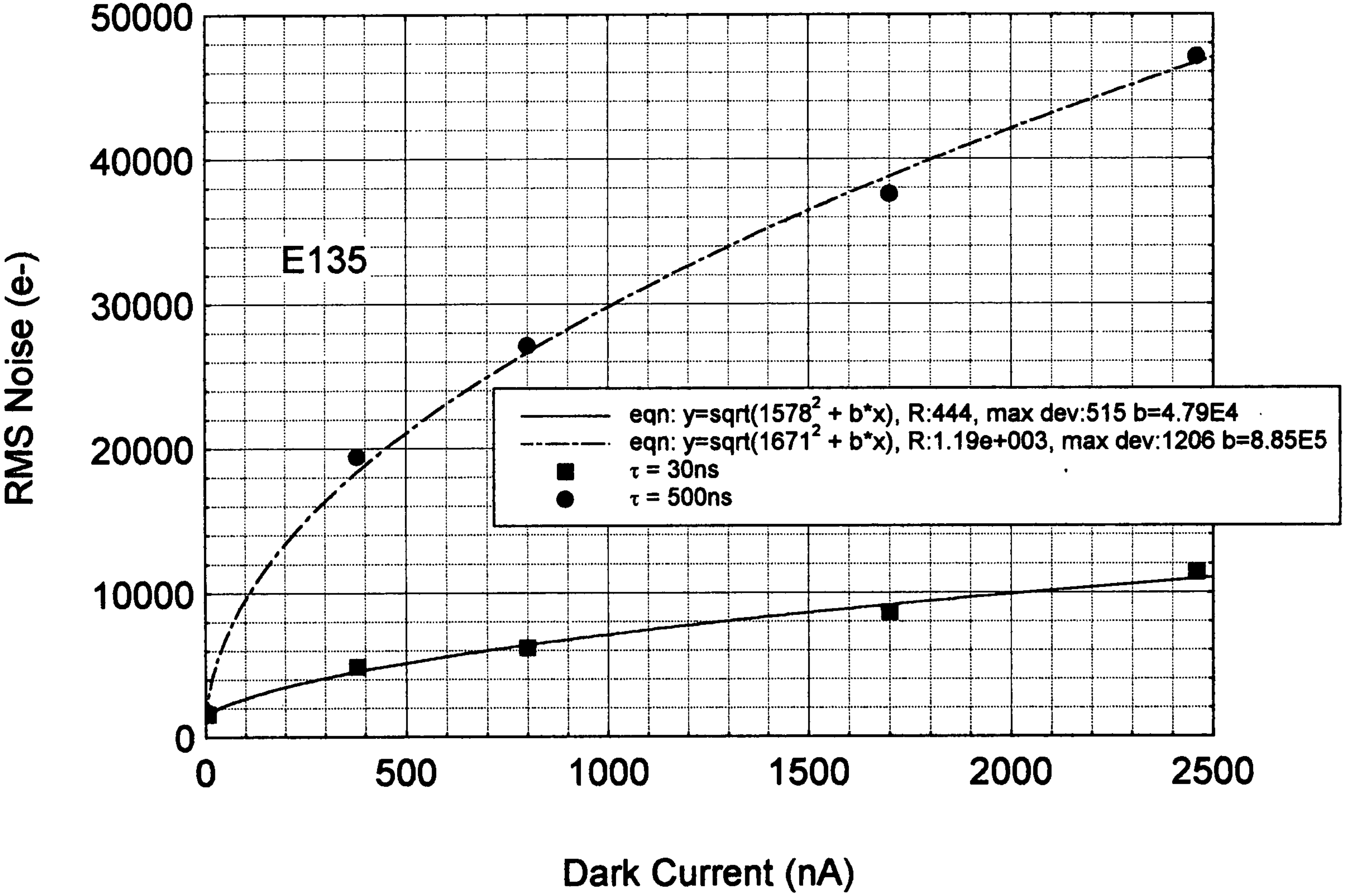

E135
RMS Noise (e-)
Dark Current (nA)
0
10000
20000
30000
40000
50000
0
500
1000
1500
2000
2500
eqn: y=sqrt(1578^2 + b*x), R:444, max dev:515 b=4.79E4
eqn: y=sqrt(1671^2 + b*x), R:1.19e+003, max dev:1206 b=8.85E5
■ τ = 30ns
● τ = 500ns

FIGURE 6

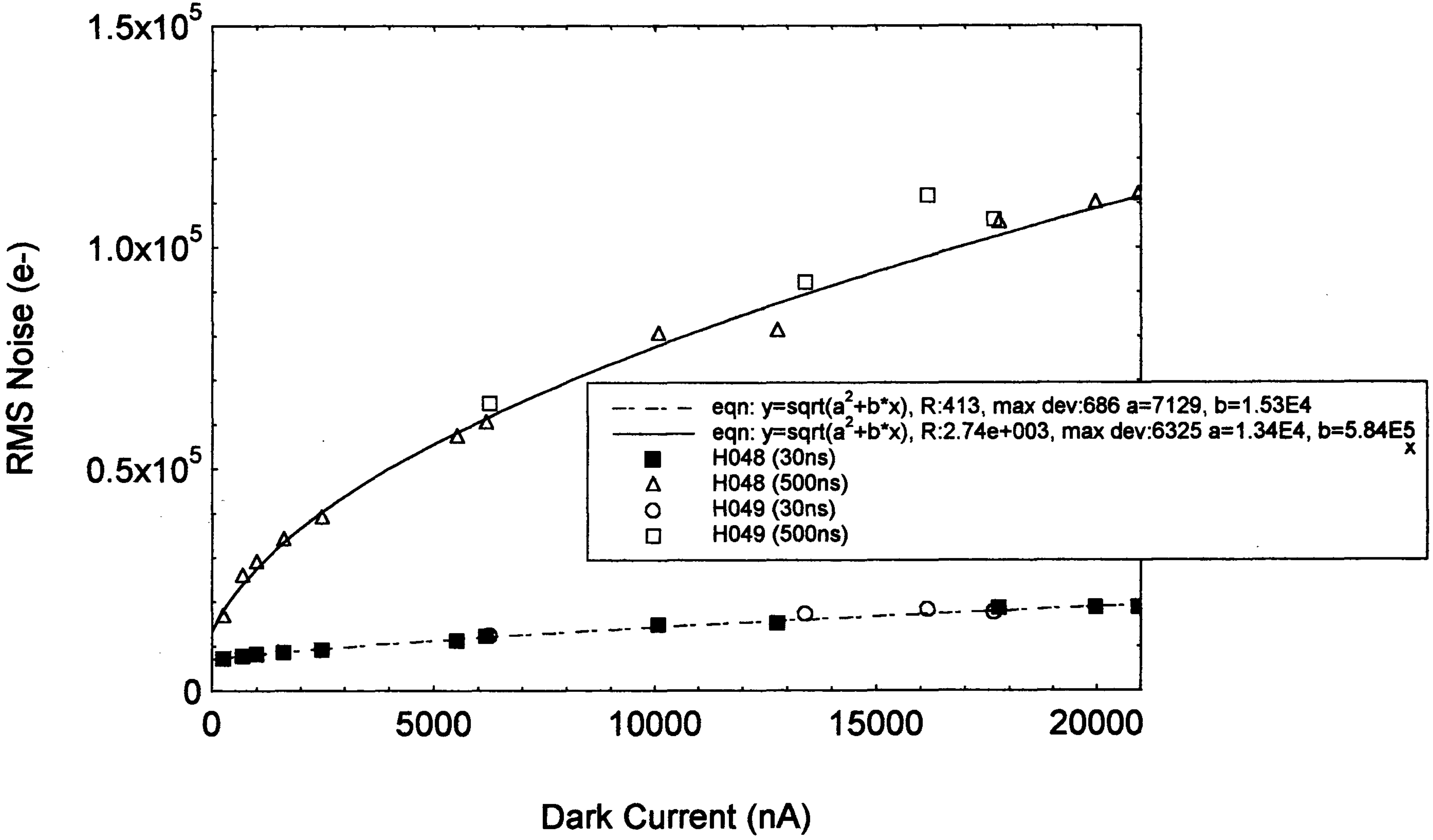

1.5x10^5
1.0x10^5
0.5x10^5
0
RMS Noise (e-)
0
5000
10000
15000
20000
Dark Current (nA)
eqn: y=sqrt(a^2+b*x), R:413, max dev:686 a=7129, b=1.53E4
eqn: y=sqrt(a^2+b*x), R:2.74e+003, max dev:6325 a=1.34E4, b=5.84E5
x
■ H048 (30ns)
△ H048 (500ns)
○ H049 (30ns)
□ H049 (500ns)

FIGURE 7

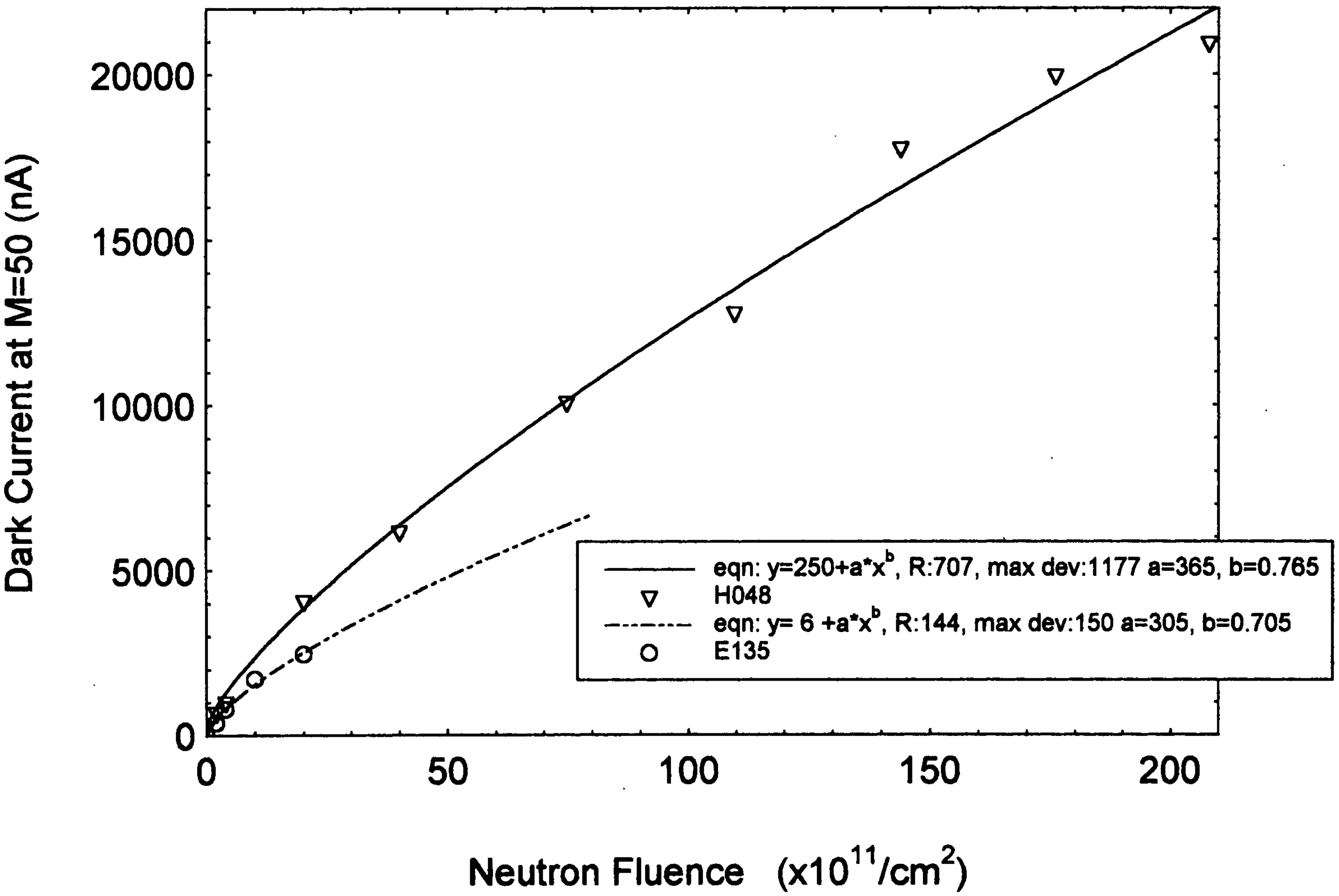

Dark Current at M=50 (nA)
20000
15000
10000
5000
0
0
50
100
150
200
Neutron Fluence (x10^{11}/cm^2)
eqn: y=250+a*x^b, R:707, max dev:1177 a=365, b=0.765
H048
eqn: y= 6 +a*x^b, R:144, max dev:150 a=305, b=0.705
E135

FIGURE 8

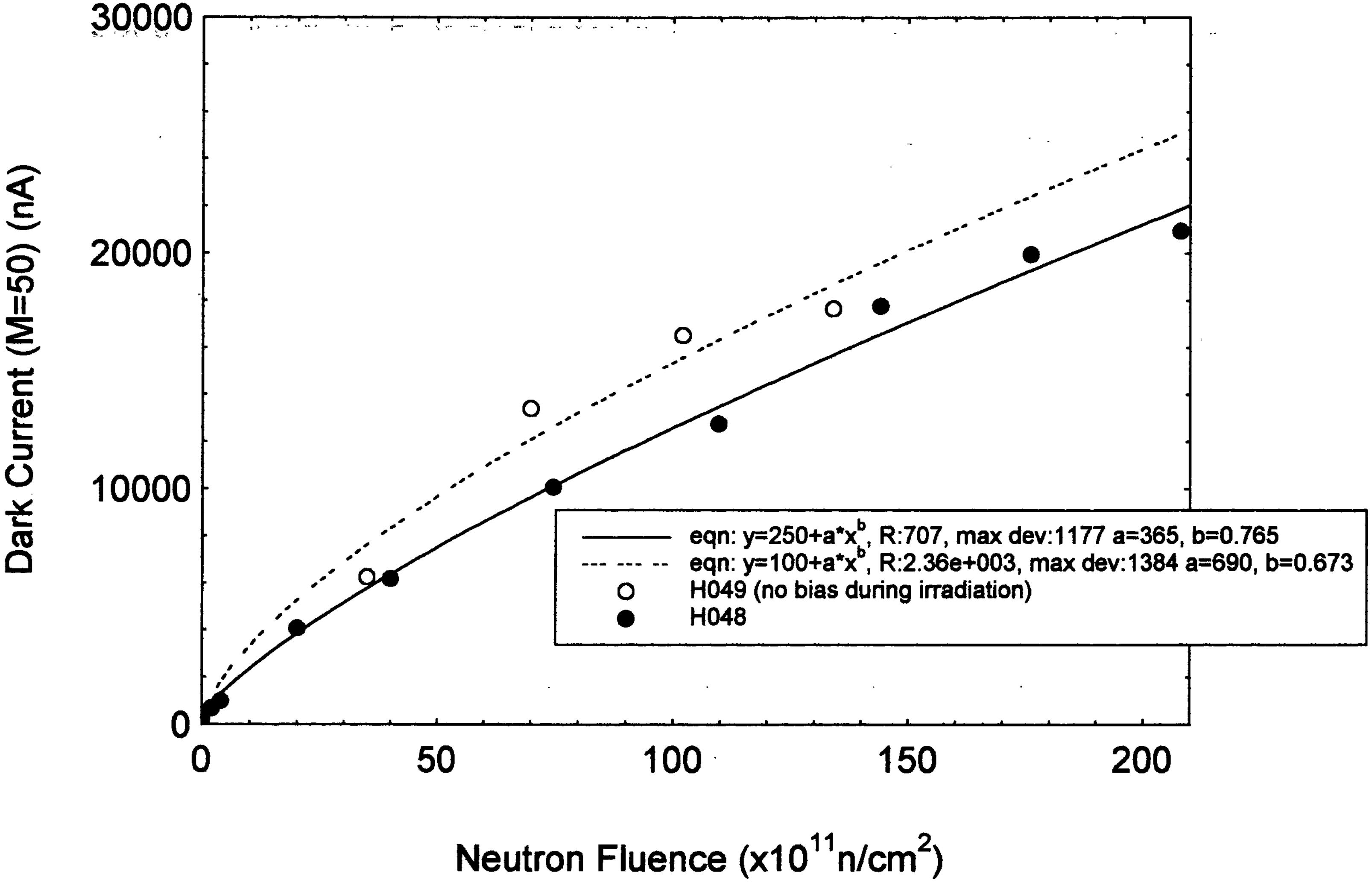

30000
20000
10000
0
Dark Current (M=50) (nA)
0
50
100
150
200
Neutron Fluence (x10^11 n/cm^2)
eqn: y=250+a*x^b, R:707, max dev:1177 a=365, b=0.765
eqn: y=100+a*x^b, R:2.36e+003, max dev:1384 a=690, b=0.673
○ H049 (no bias during irradiation)
● H048

FIGURE 9

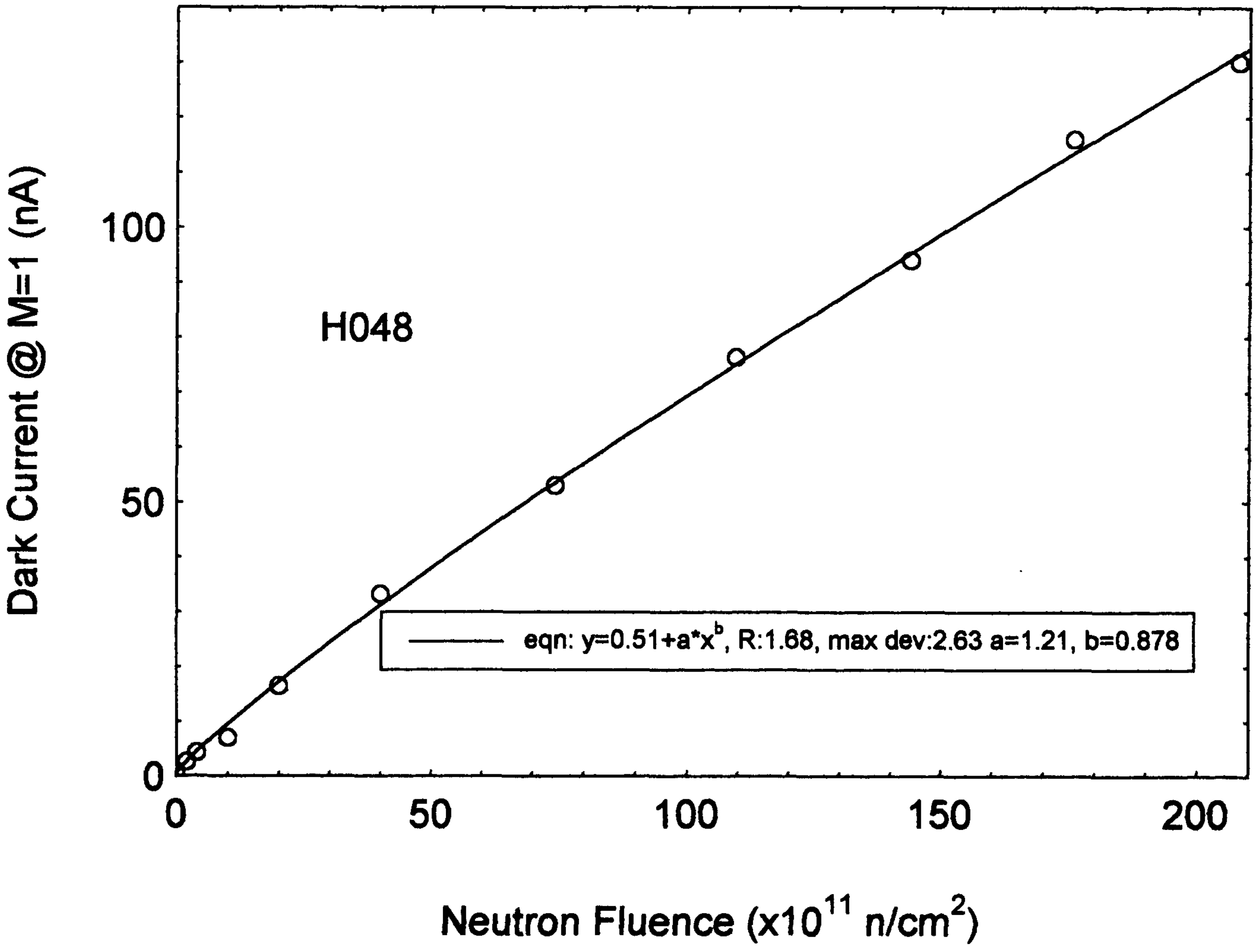
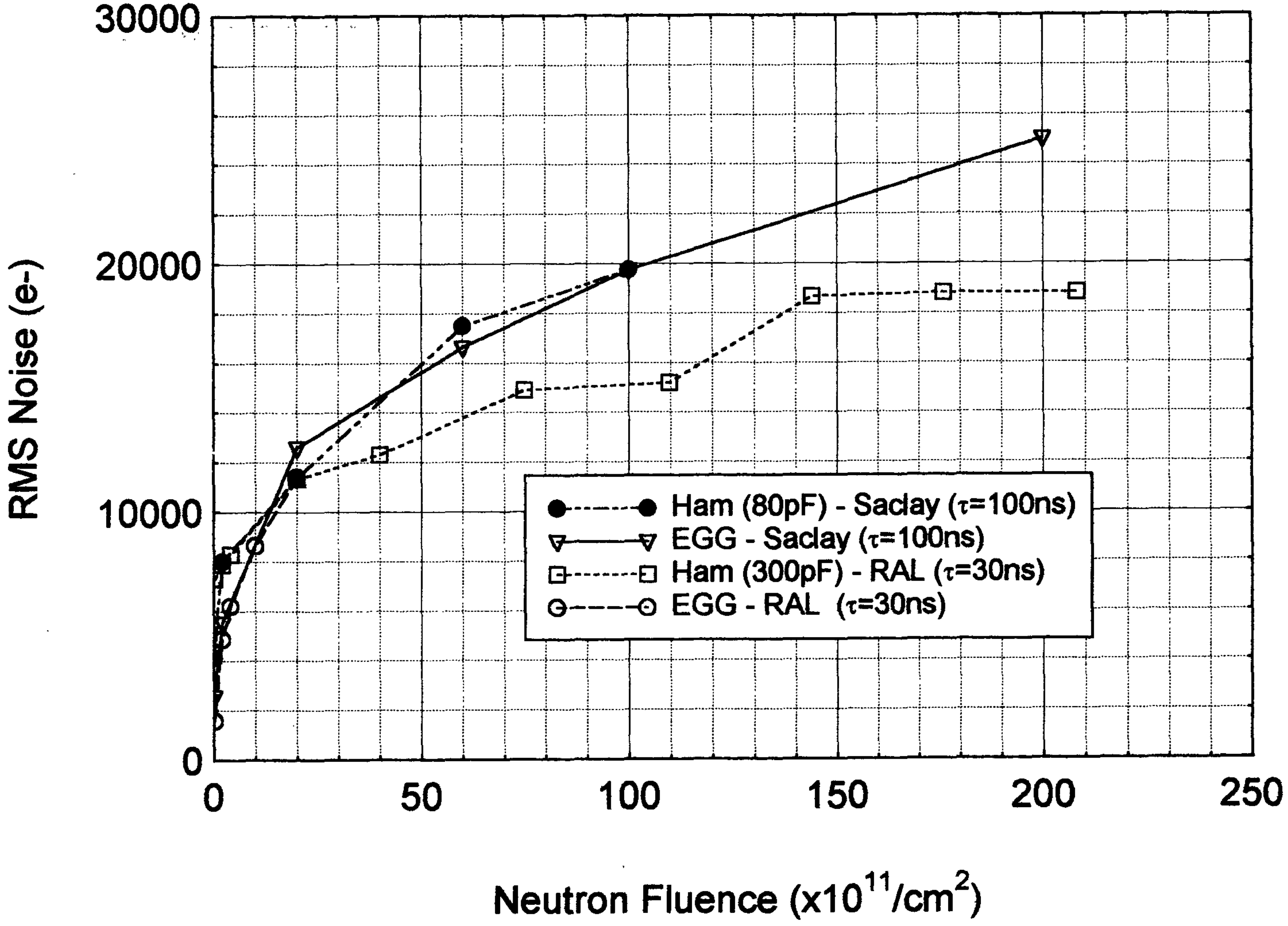

Dark Current @ M=1 (nA)
0
50
100
H048
eqn: $y=0.51+a*x^b$, R:1.68, max dev:2.63 a=1.21, b=0.878
0
50
100
150
200
Neutron Fluence (x10^{11} n/cm^2)

FIGURE 10


30000
20000
10000
0
RMS Noise (e-)
0
50
100
150
200
250
Neutron Fluence (x10^{11}/cm^2)
●------● Ham (80pF) - Saclay (τ=100ns)
▽——▽ EGG - Saclay (τ=100ns)
□------□ Ham (300pF) - RAL (τ=30ns)
○——○ EGG - RAL (τ=30ns)