**خلاصة :**

الغرض من هذا البحث هو تعيين عامل التضاعف الامثل M للحصول على احسن اداء لكاشفات الضوء . لقد استخدم البحث نوعين من انواع كاشفات الضوء ، النوع الاول من السليكون ذو تركيب $N^+\pi p\pi p^+$ والنوع الثاني مصنوع من GaAlAs .

لحساب الضوضاء الناتج من هذه المكونات استعملنا القانون التالي :

$$Si(f) = 2q I_{pho} M^x$$

المشتق بالتجربة . وفي كلا النوعين من كاشفات الضوء فان المتغير x يقع بين ٢ – ٤ معتمدا على الطول الموجي الساقط على كاشف الضوء .

يدخل هذا المتغير في حساب القدرة المكافئة للضوضاء في كلا النوعين ويكون اقل مامكن عندما تكون قيمة $x = 2$

# Determination of Multiplication Factor M for Optimum Behaviour of Avalanche Photodiodes

Tariq Albaldawi,* R. Alabedra,** G. Lecoy**

**Summary** : The purpose of this paper is the determination of multiplication factor M for optimum behaviour of avalanche photodetectors . We campare two types of avalanche photodetectors : a silicon structure R·A·P·D· $N^+\pi p \pi p^+$ and GaAl As heterostructures . In the calculation of the Noise equivalent power (NEP) of whole system we use the law $Si(f) = 2q I_{pho} M^x$ experimentally determined in the both avalanche photodetectors . The exposure x between 2 and 4 is preponderant in the NEP expression and the ideal NEP for avalanche photodetector system is obtained when x equals 2 .

https://doi.org/10.30684/etj.1983.1.7
2412-0758/University of Technology-Iraq, Baghdad, Iraq

**Introduction** : The development in Telecommunications necessitates the realisation of transmission system with very high channel capacity . Optical communication shows many advantages such as a high capacity system for transmission of information . The desired frequency ( 10 to 100 Megabit / sec ) requires photodetectors which have very high gain bandwidth product . The avalanche photodiode, in spite of its disadvantages of having inherent noise due to photocarrier multiplication process, has good sensitivity and fast response time.

The purpose of this paper is to determine the optimum value of the multiplication factor M, taking into consideration the noise characteristics of the photodetector itself and the noise present at the load resistance connected to the input terminals of the preamplifier. The two photodectors which have been used here are the silicon $N^+\pi p \pi p^+$ structure and a heterostructure type $Ga_{1-x} Al_x As$ .

## I. Noise in an Avalanche Photodetectors.

The multiplication process of carriers under the actionof an electric field in photodiodes is accompanied by a noise called multiplication noise. Many relationships have been given in the literature to determine the noise in presence of multiplication . The most interesting expression is that which gives the spectral density Si (f) of noise fluctuation current as a function of multiplication factor M and the primary photocurrent $I_{pho}$ . This relation may be represented in the following form :

$$Sid\ (f) = 2q\ I_{pho}\ M^x \ \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where x is a number lying between 2 and 4 depending on the wavelength of the incident light which determines the type of generated carriers ( holes or electrons ) in the multiplication region . In general, the generated carriers are those with the higher ionisation rate , electrons in the case of silicon . It should be mentioned that the multiplication factor M is defined as :

the ratio of the total current I which passes through the photodiode to the photocurrent in the absence of multiplication ( i.e. M = 1 ).

## 11. Noise Equivalent Power ) NEP ! :

The avalanche photodetector is always followed by a load resistance $R_L$ . A pre-amplifier is connected at the terminls of $R_L$ which can be considered to be the first element of the electronic chain used for signal processing as shownin Fig (1) .

The performance of the photodetector in the presence of weak luminous signals is affected by the inherent noise of the photodetector itself and also by the circuit connected to it . The luminous signal itself may be considered as noise generator ( noise due to the generation of electron-hole pairs created by the absorption of photons. The noise equivalent power NEP may be related to the total noise of the device under illumination by :

$$NEP = \frac{P}{I_s} \ (Si\ (f))^{1/2} \qquad \ldots \ (2)$$

**Where :**

P is the power of the luminous signal in watts .

$I_s$ is the r.m.s curren at the output in A, Si (f) is the total current spectral density of the photodiode and the circuit which follows it in $A^2$ / Hz.

Equation (2) may be rewritten , taking into conideration the sensitivity $\delta$ ( in A/W ) of the photodiode in the following form : —

$$NEP = \frac{1}{\delta} ( Si (f) )^{1/2} \qquad \dots (3)$$

The term Si (f) represents the sum of two components

$$Si (f) = Sid (f) + \frac{4 KTe}{R_L} \qquad \dots (4)$$

**Where :**

Si (f) is the noise of the photodiode given by equation (1) .

*Te is the noise equivalent temperature( noise at the input of the preamplifier )*

Relation ( 3 ) may be rewritten as :

$$NEP = \frac{1}{\delta} \left( Sid (f) + \frac{4 KTe}{R_L} \right)^{1/2} \qquad \dots (5)$$

In the presence of multiplication , the sensitivity is given by :

$$\delta = M . \delta_0 \qquad \dots (6)$$

where $\delta_0$ is the sensitivity where M = 1 .

Substituting the values of Sid (f) and $\delta$ from equations (1) and (6) into equation (5). we have then

$$NEP = \frac{1}{M \delta_0} \left( 2q \; I_{pho} M^x + \frac{4 KTe}{R_L} \right)^{1/2} \qquad \dots (7)$$

$$= \frac{1}{\delta_0} \left( 2q \; I_{pho} M^{x-2} + \frac{4 KTe}{M^2 R_L} \right)^{1/2} \qquad \dots (8)$$

When x = 2, the value of NEP decreases as M increases . Practically . the case x = 2 can never be obtained as x is always greater than 2. From this we may conclude that ( NEP ) min for a given value of M which can be obtained by :

$$\frac{d ( NEP )}{dM} = 0 \text{ which gives}$$

$$Mopt = \left( \frac{4 KTe}{q \; I_{pho} R_L ( x - 2 )} \right)^{1/x} \qquad \dots (9)$$

Taking into consideration relations (8) and (9) . the following parameters must be determined experimentally to calculate the noise equivalent power for optimum performance of the photodiode :

(1) The sensitivity $\delta$ of the photodiode .
(2) The value of x .
(3) The noise equivalent temperature Te at the input of the pre-amplifier .

### III. Minimum Detectable Power :

In the case of sinusoidal modulation , the photo-electric current has the form :

$$i\,(t) = M\, I_{pho}\,(1 + m \cos \omega t) \qquad \ldots \quad (10)$$

m is the modulation depth .

The a.c. signal with a frequency of $f = \frac{W}{2\pi}$ may br represented as :

$$i_s\,(t) = m\, M\, I_{pho} \quad \text{Cos}\omega t \qquad \ldots\ldots\ldots \ (11)$$

As the power is proportional to $i_s^2\,(t)$, hence

$$i_s^2\,(t) = \frac{m^2\, M^2}{2} I^2 \text{pho} = \frac{m^2\, M^2\, \delta o^2 p^2}{2} \qquad \ldots\ldots\ldots\ldots (12)$$

where p is the luminous power in watts.

The signal to noise ratio S/N can then be expressed as ;

$$\frac{S}{N} = \frac{i_s^2\,(t)}{Si\,(f)\,\Delta f} = \frac{m^2\, M^2\, \delta o^2\, p^2}{2\left(2qI_{pho}\, M^x + \dfrac{4KTe}{R_L}\right)\Delta f} \qquad \ldots\ldots\ldots\ldots \quad (13)$$

and

$$\frac{S}{N} = \frac{m^2\, p^2}{2\,(\text{NEP})^2\, \Delta f} \qquad \ldots\ldots\ldots\ldots (14)$$

The minimum detectable power is obtained when the S/N ratio is equal to 1, therefore from equation (14) we ha

$$m^2\, P_{min}^2 = 2\,(\text{NEP})^2\, \Delta f \qquad \ldots\ldots\ldots\ldots (15)$$

$$P\,\text{min} = \frac{\sqrt{2}}{m}\,(\text{NEP})\ \sqrt{\Delta f}\ ) \qquad \ldots\ldots\ldots\ldots (16)$$

From equation (16) we can conclude. that the minimum detectabler power Pmin is directly proportio NEP whic is at minimum when the multiplication factor M has the value of Mopt given by equation (9)

### IV : Experimental Results :

Two types of avalanche photodectors have been used here :

(1) Silicon avalanche photodiode $N^+ \pi p \pi p^+$ (1)

(2) Avalanche photodiode EROS $Ga_{1-x} Al_x As$ (4)

### IV . 1 Silicon Avalanche Photodiode $N^+ \pi P \pi P^-$

These avalanche photodiodes have been manufactured by Marcoussis Laboratory of the C.G. E. ( General companie D' Electricite') in Fance .

When using these photodiodes to detect radiation which has wavelenght $\lambda = 827$ nm . the multiplication is startedby electron injectiom

*The experimental results obtained are plotted in Figure (2). which shows the I - V characteristics for the case* where there is no radiation and for different radiation intensities We note that the dark current has no influence on the photocurrent for values of $I_{pho} > 10^9$ A.As $I_{pho}$ becomes less than $10^{-9}$A. the dark current influence can not be neglected .

The spectral density of the noise current Si (f) is plotted in Figure (3). The factor x obtained from this graph is 2.4 and the sensitivity at this wavelength ( 827nm ) is 0.2 A W.

Figure (4) shows the variation of the noise equivalent power NEP as afunction of the multiplication factor M for two values of load resistance .

When $R_L = 50$ ohms the value of Mopt is found to be 100. and when $R_l = 10^3$ ohms. $M_{opt} = 30$. As $M > M_{opt}$ the variation of NEP for the two different values of $R_L$will be the same . because the term $\underline{2q}\, I_{pho}\, M^{x-2}$ will be much greater than 4 K Te /$R_L$. i.e the inherent noise of the photodector is dominant .

Fig (5) shows clearly the influence of the primary current on the value of $M_{opt}$and the minimum value of NEP.

The influence of the factor x on the value of $M_{opt}$and the minimum value of NEP is shown in Figure (6) For the ideal case where x = 2. the multiplication factor M can be as large as possible . at least to the avalanche. but x is always greater than 2. It reaches about 2.1 -2.2 by optimization of the parameters of the photodiode .

### IV.2. Avalanche Photodiode EROS $Ga_{1-x} Al_x A_s$ (4)

This structure is manufactured by Thomson CSF ( France ).
It has the advantages of being emitter or receiver of the avalanche photodiode type. depending on the direction of bias. Its essential characteristics are a sensitivity of 0.1 A W and a dark current of 50 picoA at 0.1 V reversed biased

It should be not e d that with a radiation of $\lambda = 827$ nm and for this type of photodiodes . the multiplicat on is started by electrons, this multiplication in the GaAs and for the crystal direction <100 > is considered as an unfavorable case from the noise point of view because $\alpha < \beta$ ( $\alpha$ .and $\beta$ are the ionisation coefficients of eletrons and holes respectively )

Fig(7 )shows the variations of Sid (f )as a function of the muliplication factor M.The value of x in this case is found to be equal to 3. It will be very interesting to compare . in the same conditions of operation . the variations of NEP of these photodiodes . This is represented in Figure (8). We conclude easily that the silicon structure which acts only as a photodiode presents less noise than the Ga Al As stucture which acts as an emitter and detector . depend.i ng upon the direction of the bias voltage applied to its terminals

### Conclusion :

The optimum performance of an avalanche photodector depends essentially upon the calculation of the optimum multiplication factor $M_{opt}$. This performance is also affected by the quality of the photodetector , its dark current The primary photocrrent $I_{pho}$ and the noise characteristics of the photodetector .

It is always interesting to start multiplication process by carriers with the higher ionization rate and to produce a model which is near the ideal case where $X = 2$. The load resis tance has an influence through its noise equivalent temperature,Te.

If all these prameters are known , the optimum multiplication factor can be calculated as given in relation (9 ).

**Refrences:**

1) J.BENOIT, G. RIPOCHE, Contract D.G.R.S.T. no 72.7.0518 00.221.75.01, (1973).
2) H.KAMBE and ALL, IEEE. Trans on Electron Devices, ED-23,12, 1337 (1976).
3) M.SAVELLI and AL, Convention CNET No 76, 9B. 257.00. 790.92.45 BCJ / CPM / PMJ.
4) J.C. CARBALLES and AL, Proceeding of the 4th European conference on optical Communication September 12-15. Genova-Italy (1978).
5) R.J. Mc INTYRE, Vol ED-13, no 1, pp. 164-168 IEEE Trans on Electron Devices (1966).
6) D.RATSIRA, "Carecterisation electriqne des photodiodes a avalanche type $N^{+}\pi P \pi P^{+}$" thesis of 3rd cycle, Montpellier 1978.
7) S.M. SZE "Physics of Semiconductor Devices" Wiley 1969.
8) Tari H.SAID, "Etude et Realisation d'une chaine de Mesure de Bruit dans la Gamme 1-100 Mltz" Thesis of Docteur Ingenieur Universite des sciences et Technique du Languduc Montnellier. 1979.

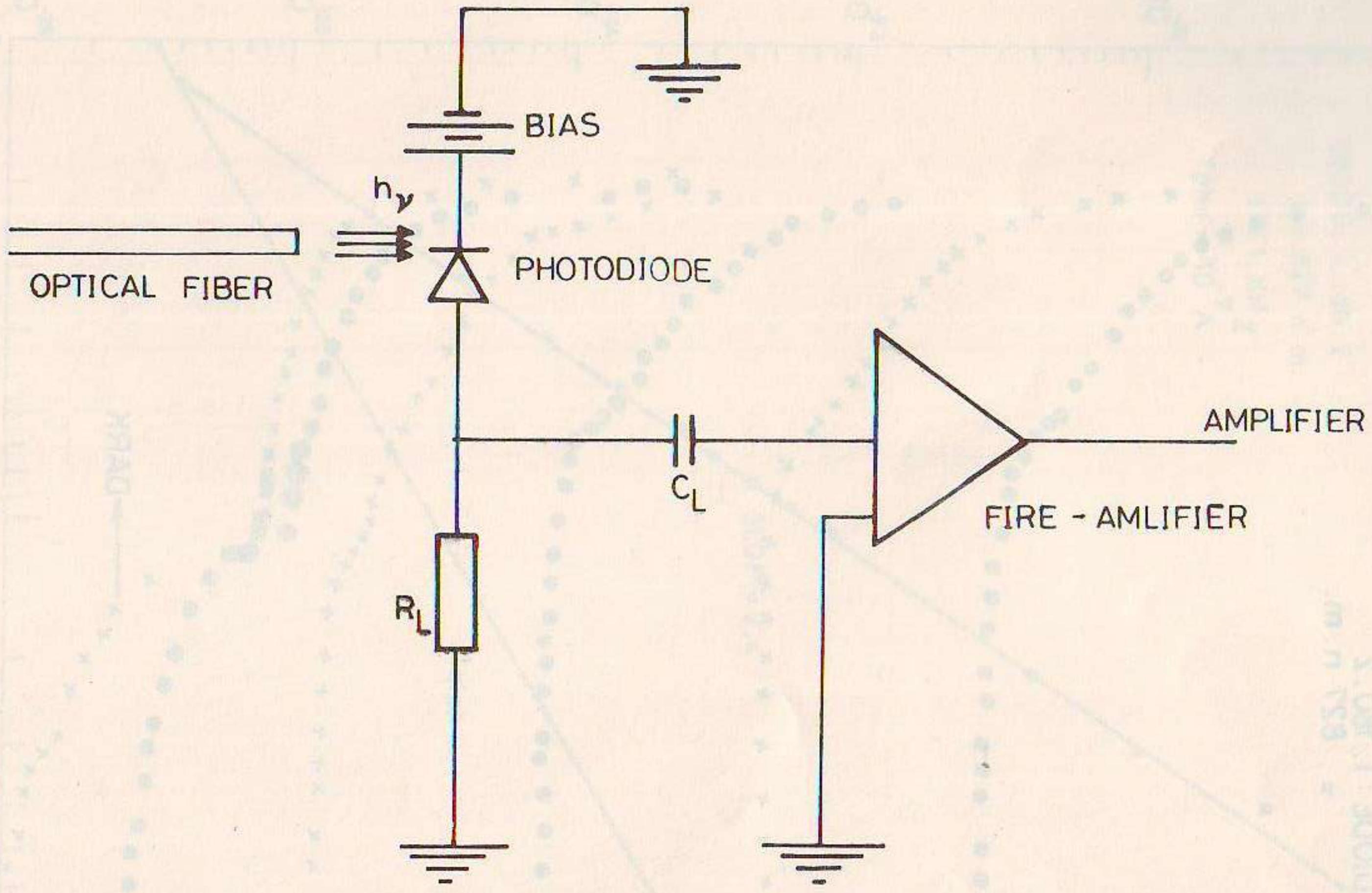
BIAS
hγ
OPTICAL FIBER
PHOTODIODE
C_L
R_L
AMPLIFIER
FIRE - AMLIFIER

FIGURE _1_

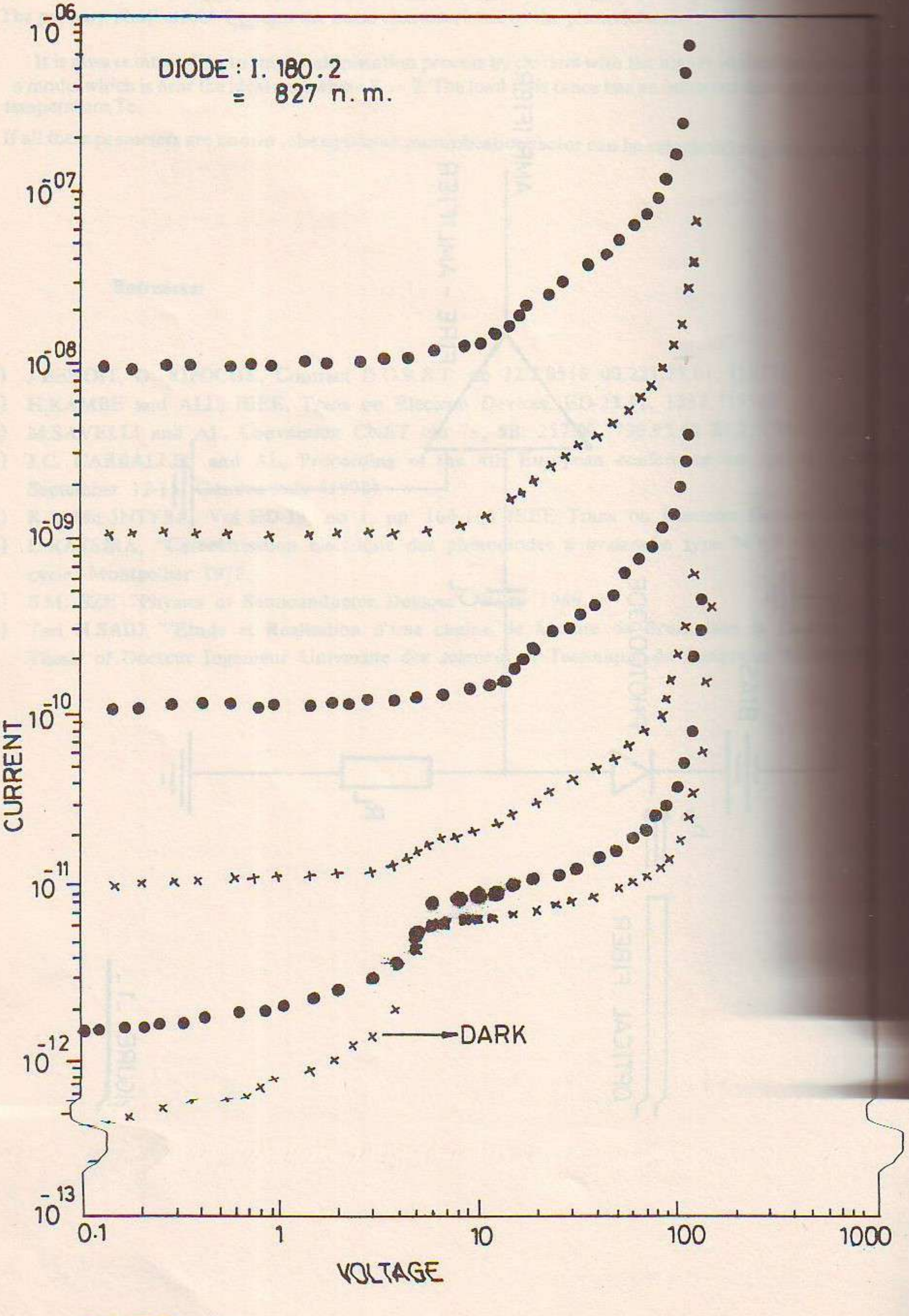
DIODE : I. 180.2
= 827 n.m.
$10^{-06}$
$10^{-07}$
$10^{-08}$
$10^{-09}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
CURRENT
DARK
0.1
1
10
100
1000
VOLTAGE

FIGURE _2_

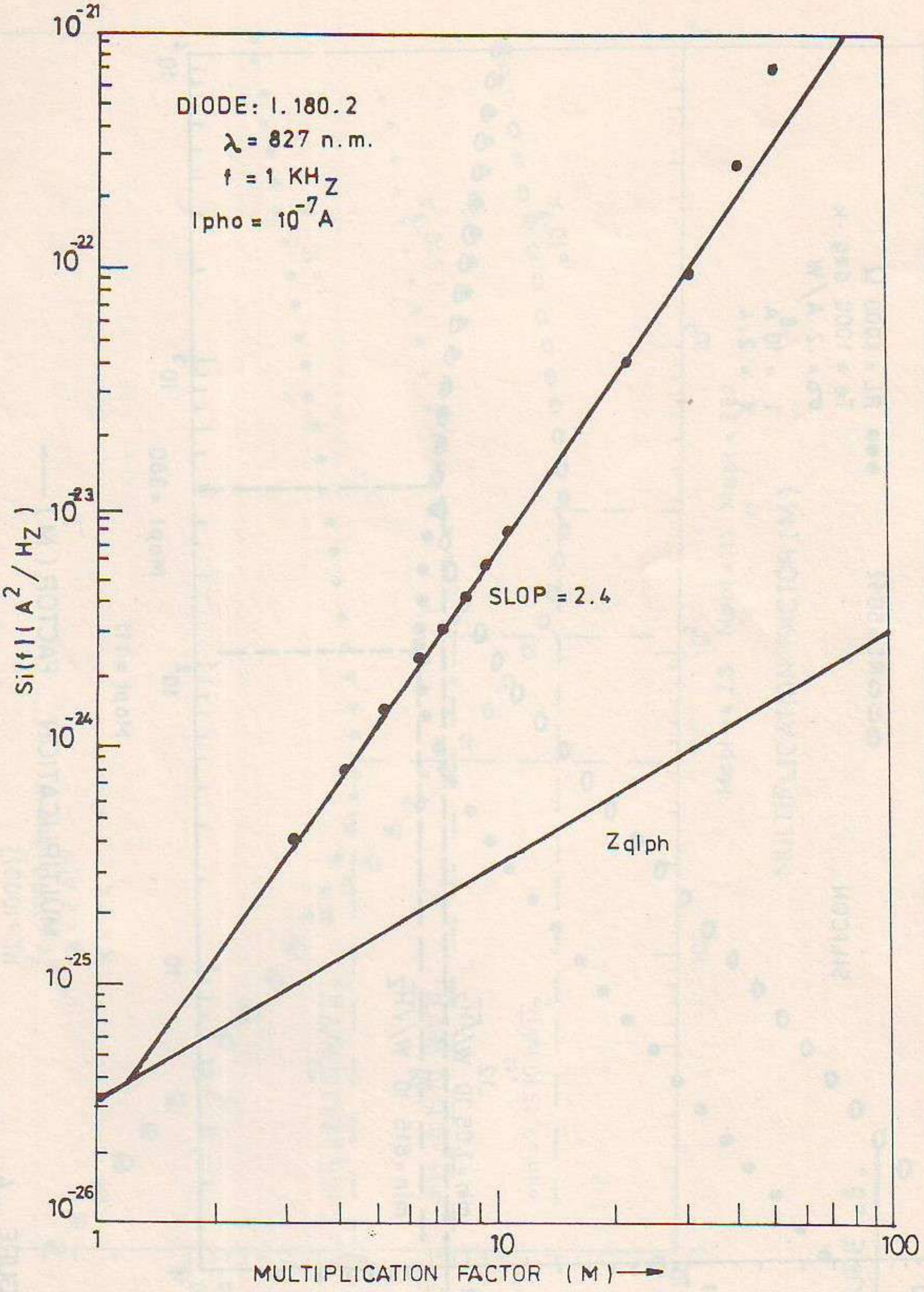
DIODE: I. 180. 2
λ = 827 n. m.
f = 1 KHZ
Ipho = 10⁻⁷A
SLOP = 2.4
ZqIph
Si(f) (A²/ HZ )
10⁻²¹
10⁻²²
10⁻²³
10⁻²⁴
10⁻²⁵
10⁻²⁶
1
10
100
MULTIPLICATION FACTOR ( M ) ⟶

FIGURE _3_

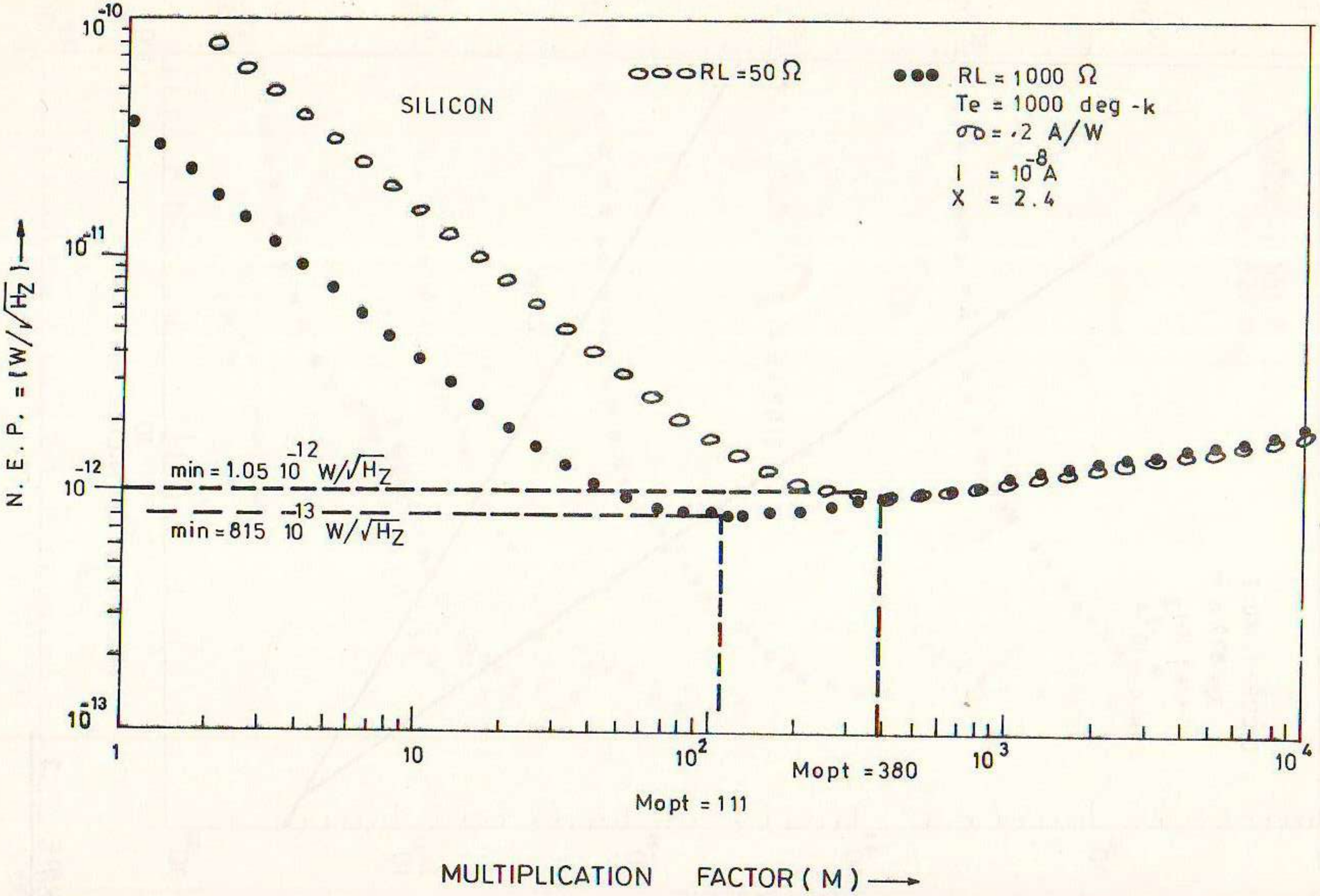SILICON
○○○ RL = 50 Ω
●●● RL = 1000 Ω
Te = 1000 deg -k
σo = .2 A/W
I = 10^-8 A
X = 2.4
min = 1.05 10^-12 W/√Hz
min = 815 10^-13 W/√Hz
N. E. P. = (W/√Hz) →
10^-10
10^-11
10^-12
10^-13
1
10
10^2
10^3
10^4
Mopt = 111
Mopt = 380
MULTIPLICATION FACTOR (M) →

FIGURE _4_

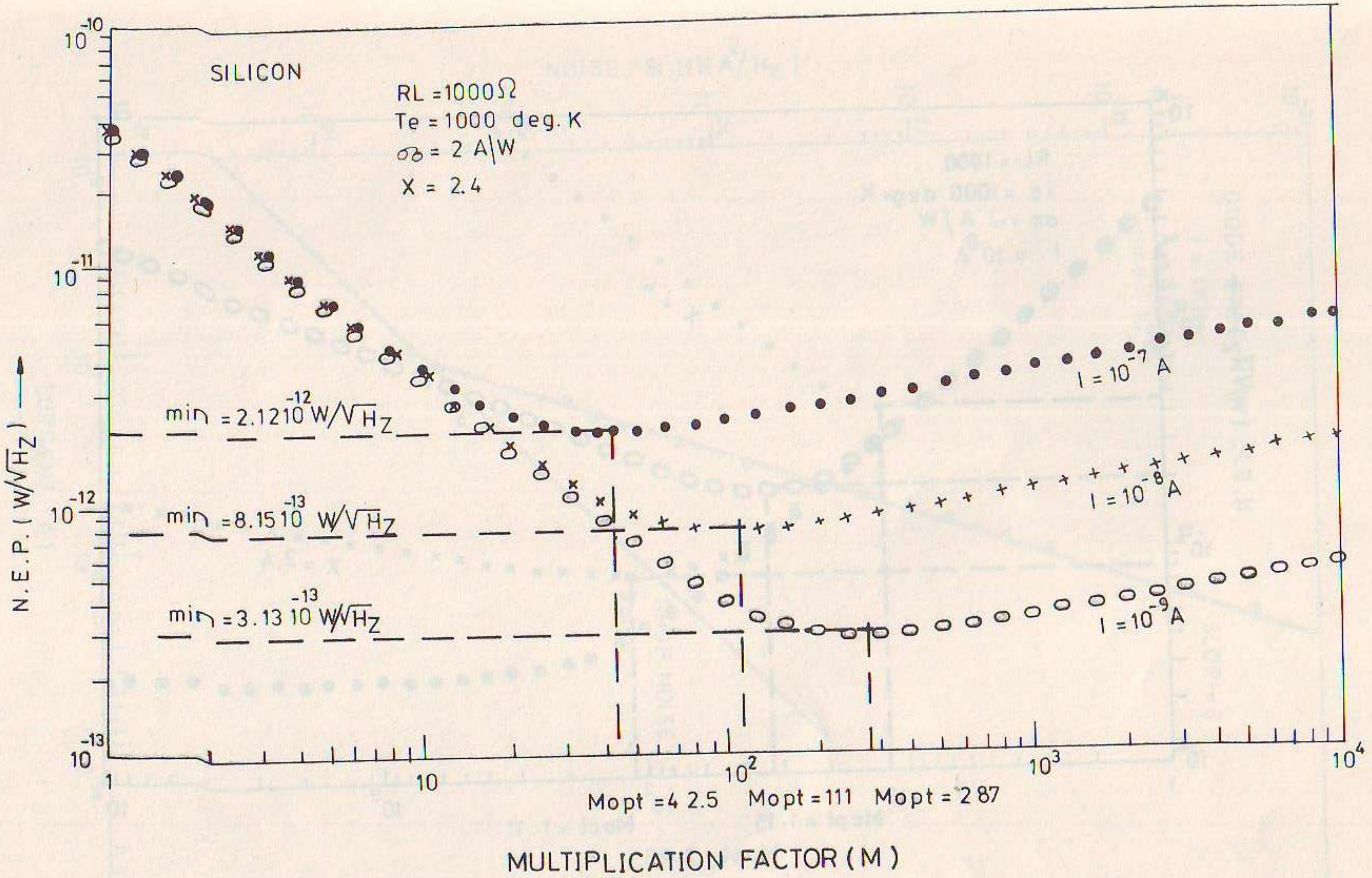
SILICON
RL = 1000Ω
Te = 1000 deg. K
σb = 2 A|W
X = 2.4
min η = 2.12 10^-12 W/√Hz
min η = 8.15 10^-13 W/√Hz
min η = 3.13 10^-13 W/√Hz
I = 10^-7 A
I = 10^-8 A
I = 10^-9 A
10^-10
10^-11
10^-12
10^-13
1
10
10^2
10^3
10^4
Mopt = 4 2.5
Mopt = 111
Mopt = 2 87
N. E. P. ( W/√Hz )
MULTIPLICATION FACTOR ( M )

FIGURE _5_

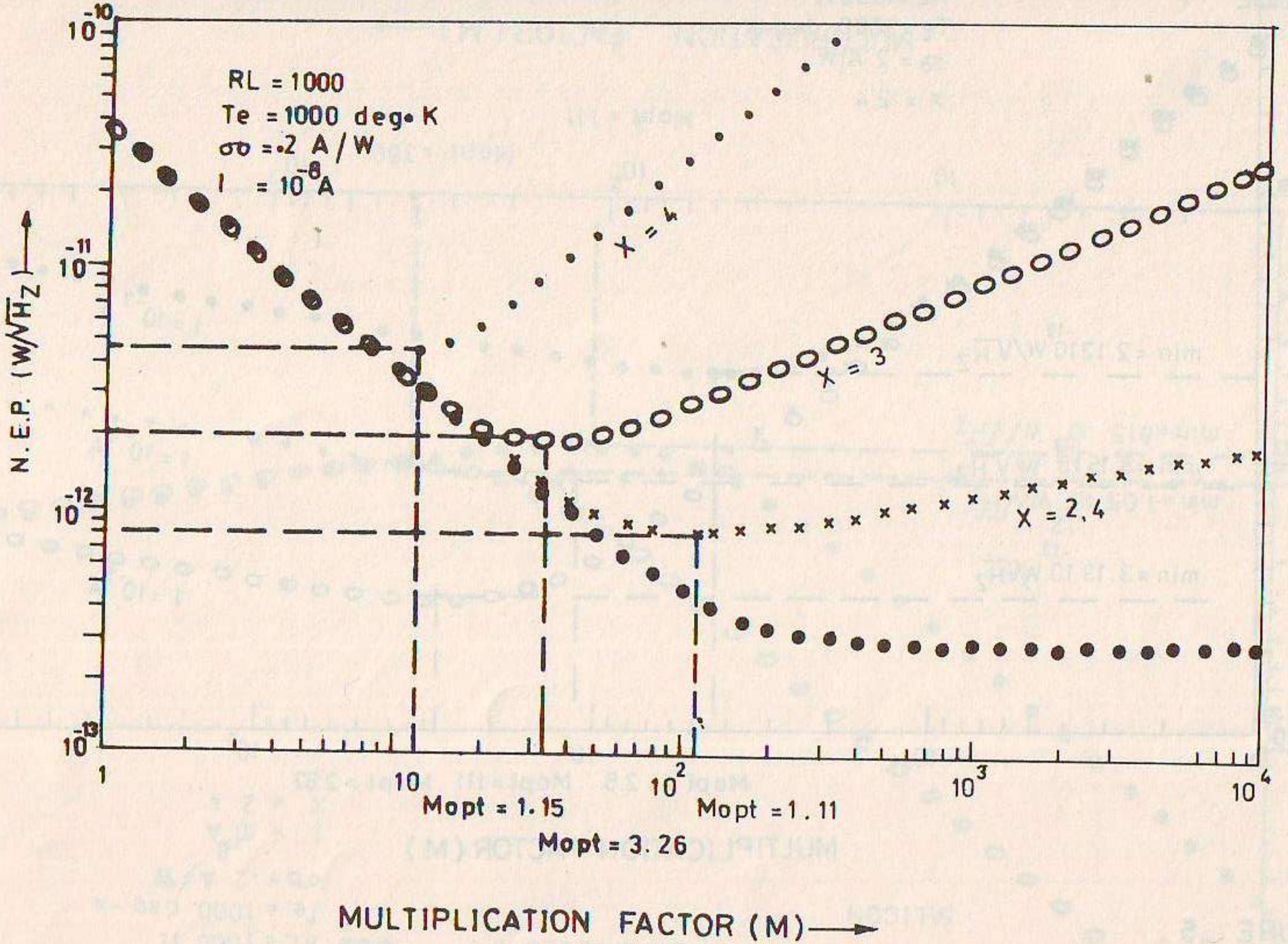
RL = 1000
Te = 1000 deg• K
σo = .2 A/W
I = $10^{-8}$ A
X = 4
X = 3
X = 2.4
N.E.P. (W/√Hz) →
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
1
10
$10^{2}$
$10^{3}$
$10^{4}$
Mopt = 1.15
Mopt = 1.11
Mopt = 3.26
MULTIPLICATION FACTOR (M) →

FIGURE _6_

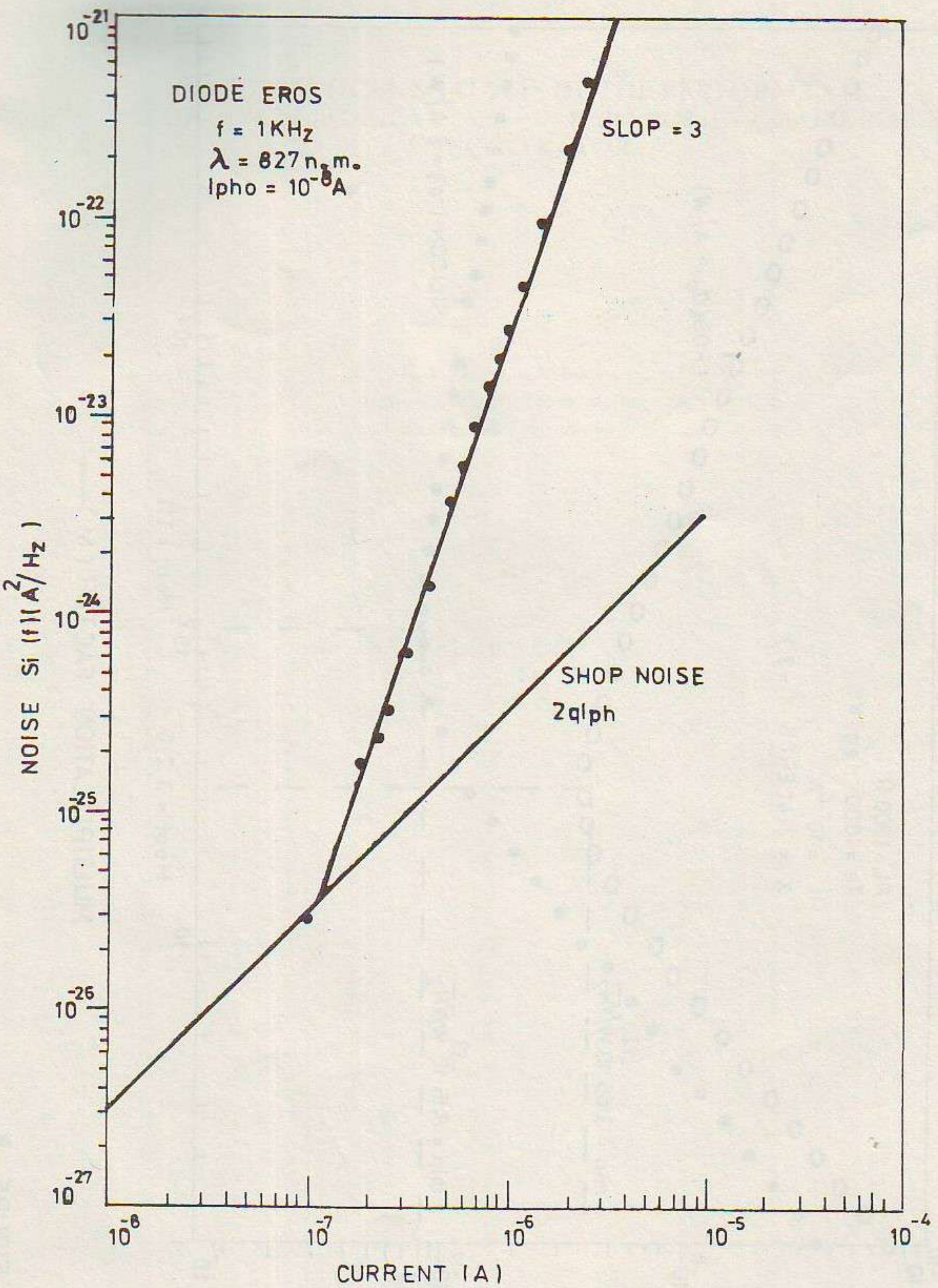
DIODE EROS
f = 1KHz
λ = 827 n.m.
Ipho = $10^{-8}$A
SLOP = 3
SHOP NOISE
2qIph
NOISE Si (f) ($A^2$/Hz)
$10^{-21}$
$10^{-22}$
$10^{-23}$
$10^{-24}$
$10^{-25}$
$10^{-26}$
$10^{-27}$
$10^{-8}$
$10^{-7}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
CURRENT (A)

FIGURE _7_

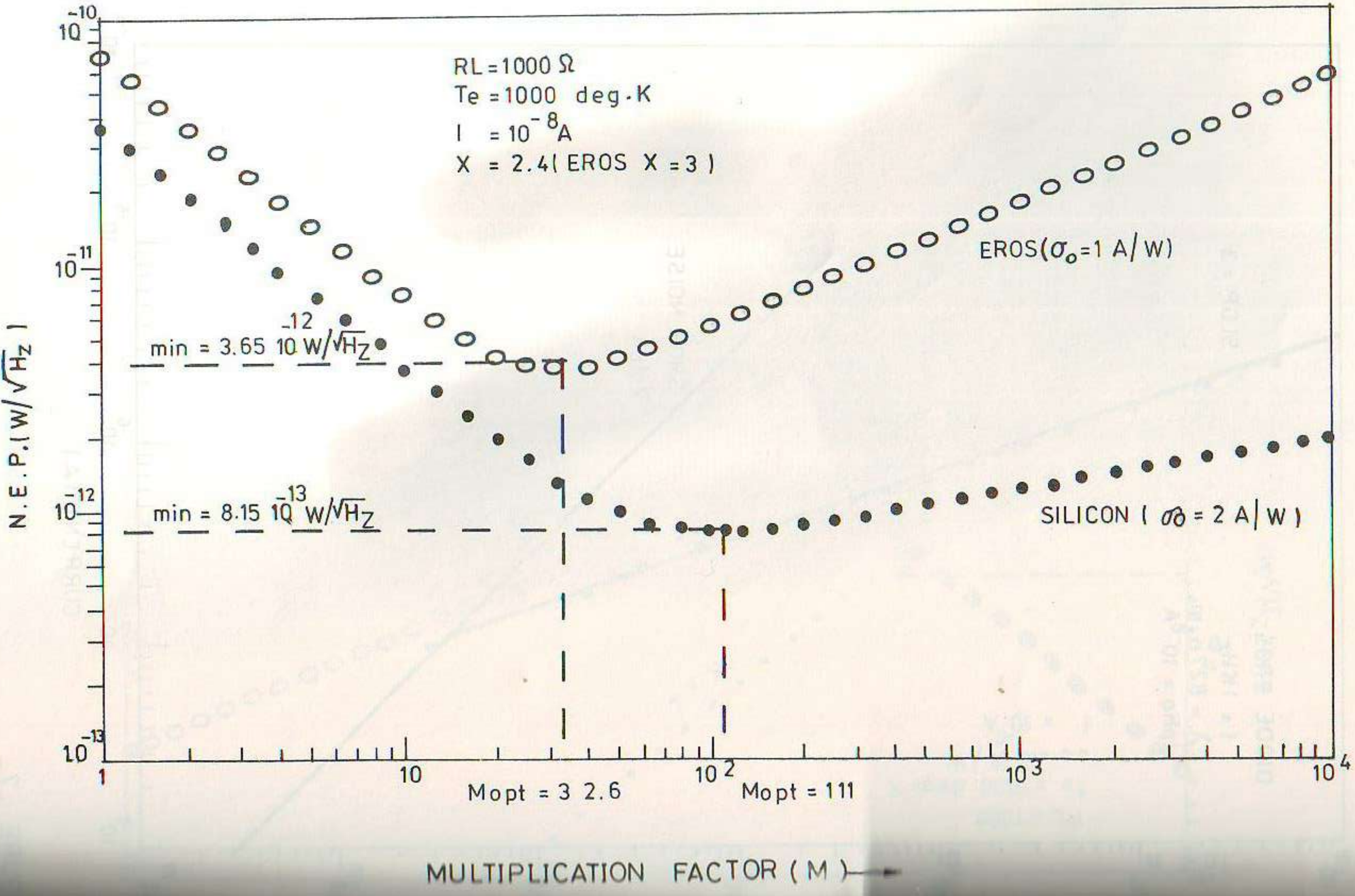
RL = 1000 Ω
Te = 1000 deg.K
I = $10^{-8}$ A
X = 2.4 ( EROS X = 3 )
EROS ( $\sigma_o$ = 1 A/W )
SILICON ( $\sigma_o$ = 2 A/W )
min = 3.65 $10^{-12}$ W/$\sqrt{Hz}$
min = 8.15 $10^{-13}$ W/$\sqrt{Hz}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
N.E.P. ( W/$\sqrt{Hz}$ )
1
10
$10^2$
$10^3$
$10^4$
Mopt = 32.6
Mopt = 111
MULTIPLICATION FACTOR ( M ) →

FIGURE .8 .