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Modeling the Dependence of Power Diode on Temperature and Radiation

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ABSTRACT

A theoretical study had been carried out on the effect of radiation on the electrical properties of silicon power diodes. Computer program "PDRAD2015" was developed to solve the diode equations and to introduce the operating conditions and radiation effects upon its parameters. Temperature increase interrupts the electrical properties of the diode in the direction of drop voltage decrease across the p-n junction. The model was analyzed under the influence of different radiation type (gamma-rays, neutrons, protons and electrons) with various dose levels and energies. The carrier's diffusion lengths were seriously affected leading to a large increase in the forward voltage. These effects were found to be function of radiation type, fluence and energy.

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1. INTRODUCTION

Semiconductor device modeling creates models for behavior of the discrete, elementary devices (transistors, inductors, diodes, etc.) based on fundamental physics, geometry, design and operation conditions [1, 2]. Also, radiation effect studies are of great interest, where electronic components and systems when exposed to the harsh radiation environments of space, or nuclear power plants and mines may degrade or even fail due to the effects of ionizing radiation. This is particularly important in reliability studies and when trying to predict the survival of these systems in space. Finally, much work had been done by the authors and others which include experimental and/or theoretical data on temperature and radiation effects in semiconductors [3-8]. So, the present paper is a trial to shed further light on such very interest and important field. In this concern, a computer program is utilized in order to characterize, and study the effects of temperature and radiation (with different types, fluencies and energies) on the electrical properties of the power silicon diodes.

2. THEORY OF OPERATION

The most important typical requirements for a power diodes are: 1) high current capability, 2) low leakage current, and 3) low forward voltage drop at high currents. Now, to analyze the forward (I-V) relationship for power diode let us examine a typical power diode model, where its physical construction are shown in Figure 1. Finally, checking the diffusion length *(L)* at high injection, one gets [9]:

$$L = (D\tau)^{1/2} = (\mu \frac{KT}{q})^{1/2} \qquad (1)$$

where :
D : diffusion constant,
τ : average lifetime of free electrons,
μ : mobility,
K : Boltzmann's constant,
T : absolute temperature, and
q : electron charge.

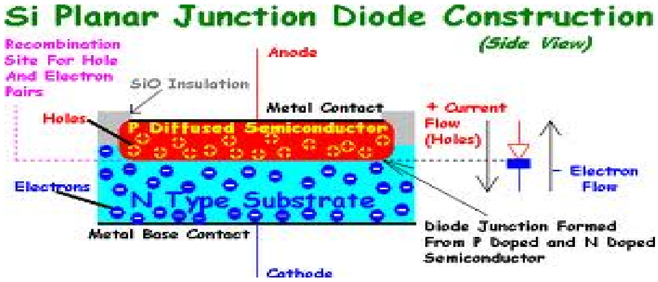


Figure 1. Physical characteristics for a typical power diode

Solving for the total voltage drop across the junction, for a certain current value (I), gives [10]:

$$V = \frac{2KT}{q} \ln \frac{IW}{2qADn_i} \qquad (2)$$

where:
W : base width,
A : area, and
n_i : intrinsic carrier concentration.

Had the diffusion length been short compared to the base width, only a portion of the base region would be in high injection. The electrons injected into the base region would recombine at a mean distance *(L)* from the junction and a majority current would flow through the very high resistance base region. However, the minority current flow through the ohmic resistance can be very high in the regions where $n > N_A$ since the resistivity of silicon for N_A=1.40x10^{14}/cm^3 is about 130 Ω/cm. A high current through this high resistivity region add significantly drop to the forward voltage. So, the forward voltage for a power diode is kept small by a long diffusion length or a long minority carrier lifetime.

3. RADIATION PHYSICS

When high energy radiation is incident on a semiconductor device, the energy is deposited in the semiconductor via two main mechanisms, atomic collisions and electronic ionizations. The relative importance of these two mechanisms in a semi-conductor depends on both the type of radiation and the nature of the device. For electrons, protons and gamma-rays environment, most of the deposited energy goes into ionization processes, i.e., excitation and pair production. For fast neutrons environment, a large fraction of the deposited energy results directly in atomic displacement damage from collisions.

The initially produced defect from gamma or electron-irradiation is quite simple and can be expressed as a single displaced lattice atom and its associated vacancy *(Frankel* Defect [11]). On the other hand, irradiation with fast neutrons produce regions of damage, each contains several hundred displaced atoms. Hence, the interaction of radiation with semiconductor crystals is simply described by the number of defects/cm^3 created [12].

It can be shown that point defects *(Frankel* Defects) result in the introduction of allowed energy states within the forbidden gap of the semiconductor [13] which affects mainly the minority carriers lifetime. The degradation in minority carrier lifetime is usually expressed as:

$$d(1/\tau) / d\Phi = K_\tau, \qquad (3)$$

where, K_τ is the lifetime damage constant, and Φ is the radiation fluence.
Some literatures discuss a diffusion length damage as:

$$1/L_f^2 = 1/L_0^2 + K_L\emptyset \qquad (4)$$

Where, L_f, and L_0 are the diffusion length after and before irradiation, and K_L is the diffusion length damage constant.

The effects of radiation on the power diode performances is mainly due to the change in lifetime of minority carriers contained in the base region, which obeys the relations mentioned above. In this concern, typical published values for the diffusion length damage constant (K_L), for protons and electrons are illustrated in Table 1 [14, 15]. On the other hand, for neutrons, it is observed that the damage constant is a function of the injection ratio (n/p) and has the values listed in Table 2 [16, 17]. Finally, for gamma-radiation, it is found that for cobalt-60, the diffusion length damage constant has a value of $1.27x10^{-11}$ particles^{-1} [18, 19].

Table 1. Diffusion length damage constant due to electrons and protons

Energy [MeV]	Electrons [Particles^{-1}]	Protons [Particles^{-1}]
1	1.0×10^{-10}	**3.8×10^{-5}**
10	2.7×10^{-10}	**3.8×10^{-6}**
50	4.0×10^{-10}	**8.5×10^{-7}**
100	5.0×10^{-10}	**4.7×10^{-7}**

Table 2. Diffusion length damage constant due to neutron irradiation

Injection ratio	Damage constant [Particles^{-1}]
10^{0}	**7.80×10^{-9}**
10^{-4}	**7.40×10^{-8}**
10^{-6}	**1.47×10^{-7}**

4. RESULTS AND DISCUSSIONS

Results obtained by Rageh, et al. [20] have been analyzed using the proposed computer program (Appendix A) for calculating the diffusion length at high injection level and plotting the forward (I-V) relationship.

The effect of different radiation types (gamma-rays, electrons, neutrons and protons), fluence (from 1.0x108/cm2 up to 1.0x1020/cm2) and energy (from 1.0 MeV up to 100 MeV) are studied. Also, the effect of temperature variation (in the range from 300 K up to 800 K) is considered.

4.1. Temperature Effects

The forward (I–V) characteristics of the silicon power diode is calculated using the relation mentioned in Eq. 2, where it is well known that both; voltage temperature coefficient (KT/q) and the intrinsic concentration of electrons (n_i) are temperature dependent [21]. In this concern, Figure 2 shows the effects of temperature on the electrical properties of silicon power diode calculated using the proposed program. The (I–V) curves shift profoundly towards the low values of drop voltage for the same forward current values, the matter which was shown to be in close agreement with work done by X. Kang, et al., and published at online Electronics Guide [22, 23].This effect, of course, is due to the increase in the voltage temperature coefficient and the intrinsic carrier's density of the minority electrons contained in the base region of the diode with increasing the temperature [21]. From which, a linear dependence of forward voltage on temperature was obtained, as well, as empirical equation could be deduced as:

$$V = 1.37554 - 0.0015\ T \qquad (5)$$

where, V is the forward voltage, and T is the temperature in Kelvin.

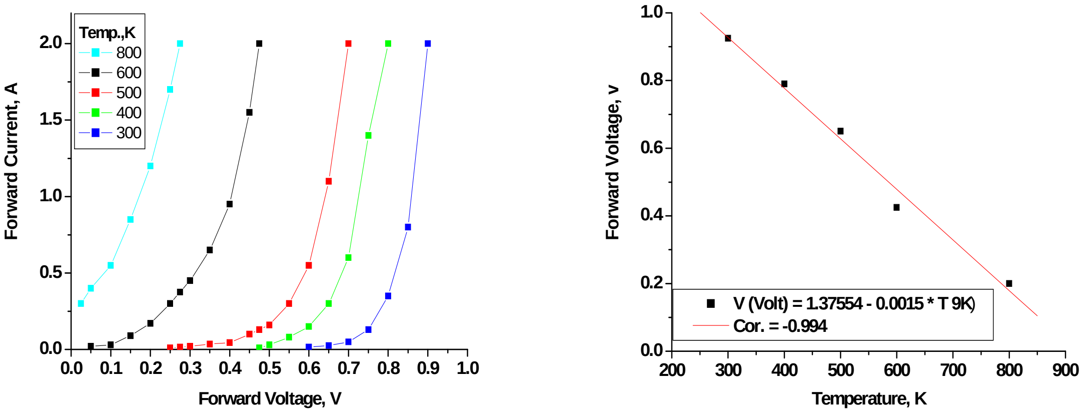
4.2. Radiation Effects

Permanent radiation damage in silicon power diodes is mainly attributed to the change in the minority carriers lifetime. Consequently, the mean diffusion length of the carriers also changes. So, during the present study, different radiation types were used and the corresponding damage effects on the diffusion length are represented in Figure 3. A pronounced reduction in the diffusion length occurs from its initial value (137 µm) down to a certain value which depends on radiation type, fluence and energy.

The results are plotted for the different types of radiation, where it is noticed that radiation fluences more than 10^9/cm^2 are shown to be effective, where it was found that a close agreement with those results published by Carlson, et.al [24] was obtained. Damage due to proton irradiation is shown to be very strong especially in the low energy band. For comparison, using a constant proton fluence of 10^{13}/cm^2, the diffusion length was reduced to 48 µm and 130 µm for proton energies of 1.0 MeV and 100 MeV respectively. This phenomenon, of course, does not hold for the case of electron irradiation, where the damage is shown to be a direct function of both radiation fluence and energy.

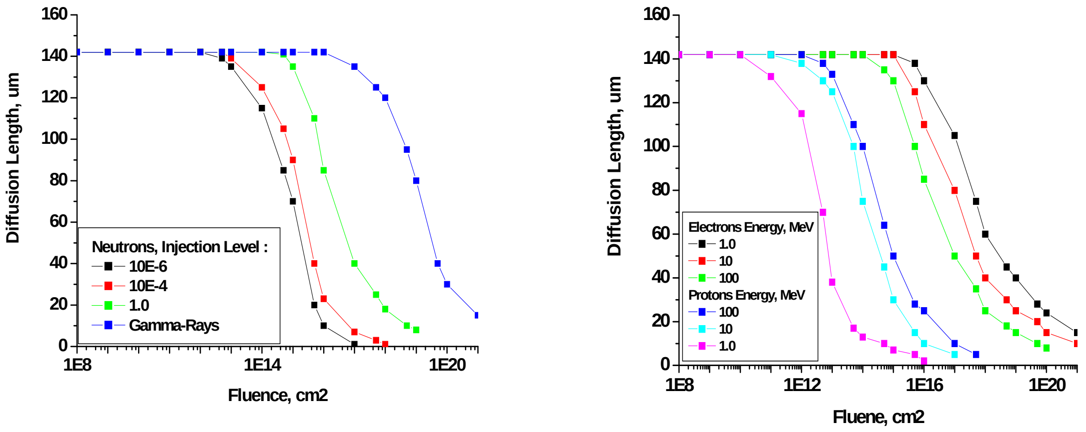
In case of neutron irradiation, the damage occurs strongly for fluences above 10^{13}/cm^2 depending upon the injection ratio (n/p). Finally, gamma-rays produce the same damage on the diffusion length at fluences higher than 10^{17}/cm^2.

The above mentioned damages are attributed to what is called "displacement cross-section" for the radiation type and energy. Figure (4) indicates that the displacement cross-section for both gamma-and-electron-radiation is a direct function of the energy [11, 12]. On the other hand, protons are charged particles, similar to electrons, and it might be expected that both produce the same degree of damage. This is not the case, because proton has larger mass and it can impart much more energy to the nucleus than an electron when collisions with lattice occur.



(a) (b)

Figure 2. Effects of temperature on the forward (I-V) characteristic curves of Si-power diode (a) and the linear dependence of the forward voltage on temperature, calculated applying the developed computer programming (b)



(a) (b)

Figure 3. Effects of radiation with different types, fluencies and energies on the diffusion length of the silicon power diode {(a)- Neutrons and gamma-rays, and (b)-electrons and protons)}.

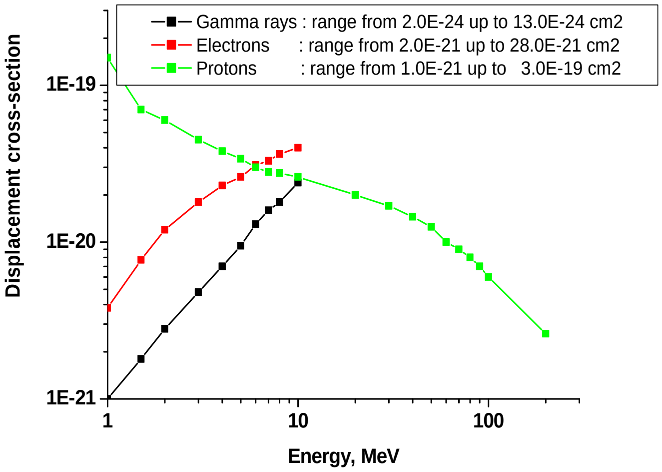


Figure 4. Displacement cross section versus energy for silicon, different radiation types are shown (compiled by the author).

For protons with higher energies, most of the energy may be transferred into kinetic energy and a decrease in the displacement cross-section occurs due to the decrease in the possibility of proton capturing.

Sheng, S.L. [25] has performed numerical calculations of the total diode voltage drop as a function of the ratio *W/L* for both ohmic and majority carrier contacts. Their results for the investigated silicon power diode are considered.

The diffusion length, after exposure to radiation, can be obtained from the minority carrier lifetime as:

$$L = D\tau^{1/2} = \left(\frac{D}{R}\right)^{1/2} = \left(\frac{D}{R_0 + k\tau\, \emptyset}\right)^{1/2} \qquad (6)$$

where, R and R_0 are the recombination rates after and before irradiation, and Kτ is the minority carrier lifetime damage constant.

On the other hand, the diode voltage is given in Figure 5 in terms of the voltage without injection or I(eW/A) [20], where:

$$Ir = I(eW/A) = I\ W/q\mu AN_A \qquad (7)$$

Hence, from Figure 5, for the value of Ir and W/L, applied voltage can be obtained at various operating conditions.

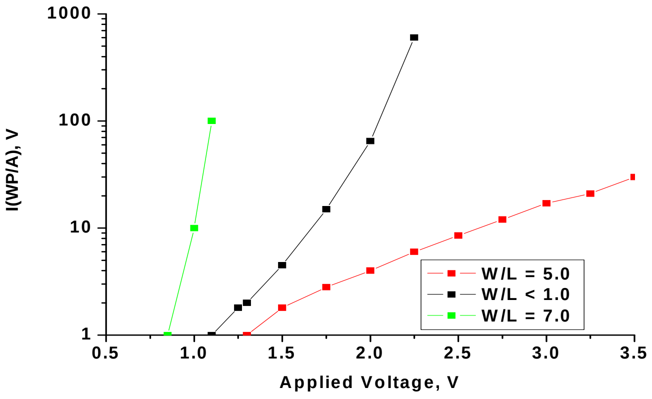
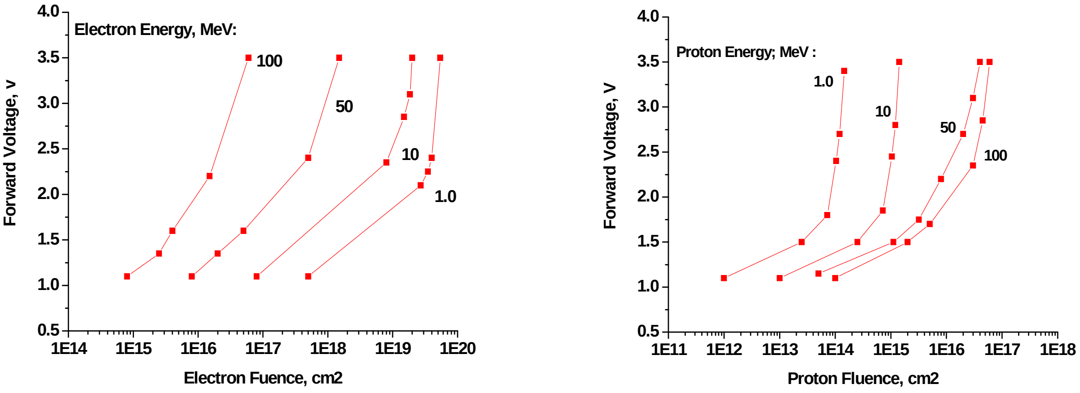


Figure 5. Voltage-current relations for N^+PP^+ power diode.

The obtained results, after introducing the effects of radiation, on the equations mentioned above, are shown in Figures 6 through 8. A large increase in the forward voltage value is shown for the same forward current, closely identical with the results published by J.R.Srour [26]. This increase is a function of; radiation type, energy and fluence. It is so easy to notice that for all the radiation processes, the device loses its main features as a rectifying device and behaves as a linear resistance at a certain radiation fluence. As an example, for electron (with energy of 1.0 MeV) with fluence value of 5.4x10^{19}/cm^2 results in the device complete damage. Increasing the energy of the incident electrons up to 100 MeV causes the diode breakdown at less fluence levels (9x10^{18}/cm^2). Moreover, diode failure due to proton irradiation occurs at 1.54 x10^{14}/cm^2 and 1.1x10^{17}/cm^2 for proton energies of 1.0 MeV and 100 MeV respectively.

Higher gamma-fluences are shown necessary to affect the power silicon diode performances (Fig. 8). A threshold fluence value of 5.0x10^{18}/cm^2 is just required to increase the forward voltage from its initial value of 0.8 V (at 0.3 A of forward current) up to 1.05 V and a fluence value of 4.25x10^{20}/cm^2 is enough for diode forward failure.



(a) (b)

Figure 6. Effects of electron (a)- and proton (b) -irradiations with different fluences and energies on the forward voltage of the silicon power diode (I_F = 0.3 A).

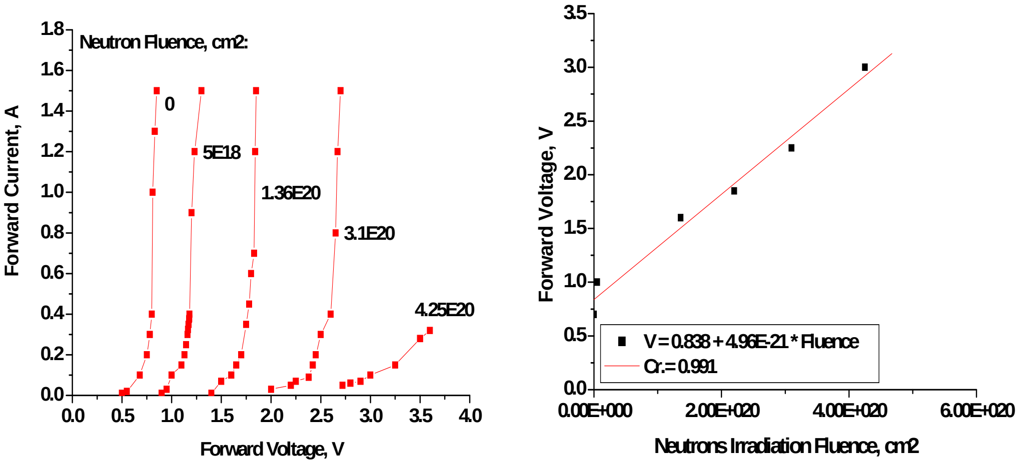


Figure 7. Effects of neutron irradiation on the forward voltage drop of silicon power diode (I_F = 0.3 A).

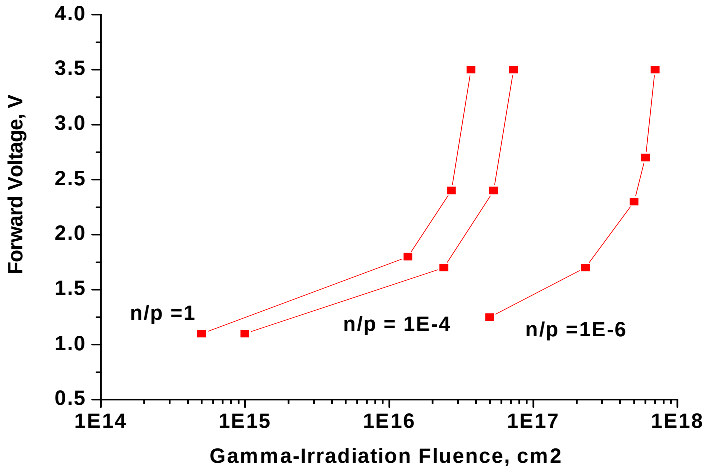


Figure 8. Effects of gamma irradiation with different fluences on the forward voltage drop of the silicon power diode (I_F=0.3 A).

Finally, Figure 9 shows a comparison for the calculated changes in forward voltage values due to radiation exposure with different type, energy and fluence.

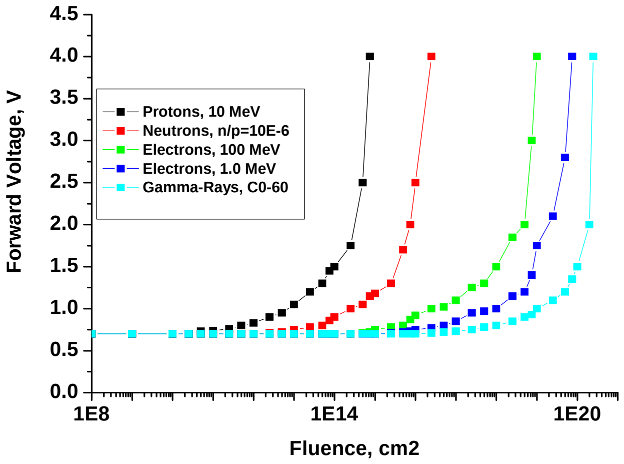


Figure 9. Calculated change in forward voltage values due to radiation exposure with different type, energy and fluence.

5. CONCLUSION

A computer program has been developed to analyze the characteristics of power silicon diode under the influence of various radiation types and temperature variation conditions. From which, it was found that increasing the device temperature interrupts its (I-V) curves in the direction of decreasing the forward voltage for the same forward current values. As well, an increase in the integrated radiation flux causes a monotonous increase in the forward voltage and differential resistance and the silicon diode tends to become a linear high ohmic resistor.

Irradiation with low energy protons has strong effect where the device is completely damaged at $1.45\text{x}10^{14}/\text{cm}^2$. On the other hand, gamma-rays emitted from cobalt-60 source causes the same defect on devices at $4.25\text{x}10^{20}/\text{cm}^2$. On the other hand the damage effect caused by electrons and neutrons irradiation lies between that obtained by protons and gamma. All defects are shown to be function of radiation type, fluence and energy.

Appendix A

The following program has been developed by the authors to carry out the calculations of power diode characteristics under different operating conditions of temperature and radiation exposure. As well, here follows the definitions of the symbols used in the mentioned program:

WOL:	W/L
NA:	N_A
UN:	mobility
KTOQ:	KT/q
AKL:	diffusion length damage constant
RAD:	radiation fluence
LF:	diffusion length after irradiation
DN:	diffusion constant

```
10    REM PROG "PDRAD2013"
20    OPTION BASE 1
30    DIM  I(30), IR(30), RAD(3O), Z1(3O),
      Z2(3O), Z3(30), Z4(30)
40    DIM Z5(30), Z6(30), Z7(30), LF(30),
      WOL(30), V(30).
50    Q = 1.6 E -19
60    UP = 500
70    A = 0.01
80    NA = 1.2 E 14
90    L = 0.000137
100   W = 0.000095
110   TINF = 0.000005
120   ND = 1.0 E 9
130   UN = 1440
140   K = 1.38 E -23
150   DN = 37
160   FOR J = 1 TO 21
170   READ I(J)
180   NEXT J
190   DATA. 05, .1, .2, .3, .4, .5, .6, .7, .8, .9,1, 1.1,
      1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0
200   FOR J = 1 TO 13
210   READ RAD(J)
220   NEXT J
230  DATA 1E8, lE9, 1El0, lEll, lEl2, lEl3, lE14,
     1E15, lE16, lE17,1E18, lE19, lE20
240  INPUT T
250  INPUT AKL
260  IF T = 250 THEN 270 ELSE 290
270  NI = 1.7 E 8
280  GOTO 460
290  IF T = 300 THEN 300 ELSE 320
300  NI =1.5E10
310  GOTO 460
320  IF T = 400 THEN 330 ELSE 350
330  NI = 8 E 12
340  GOTO 460
350  IF T = 500 THEN 360 ELSE 380
360  NI = 4E14
370  GOTO 460
380  IF T = 600 THEN 390 ELSE 410
390  NI =5E16
400  GOTO 460
410  IF T = 700 THEN 420 ELSE 440
420  NI =2.5E16
430  GOTO 460
440  IF T = 800 THEN 450 ELSE 470
450  NI = 2.0 E 17
460 LPRINT "T =";T;"NI=";NI
470  KTOQ = KT/Q
480 Z4 = 2 Q * A * D * NI
490  FOR J 1 TO 21
500  Z5(J) = I(J)/W
510  Z6(J) = Z5(J)/Z4
520  Z7(J) = LOG(Z6(J))
530   V(J) = 2* KTG(OQ * Z7(J)
540  NEXT J
550  LPRINT "******************"
560  FOR J = 1 TO 21
570  LPRINT J, I(J), V(J)
580  NEXT J
590 LPRINT "AKL = ";AKL
600  FOR J = 1 TO 13
610 Z(J) = (AKL * RAD(J))*(L**2)
620 Zl(J) = 1 + Z(J)
630   Z2(J) = (L**2)/Zl(J)
640  Z3(J) = SQR(Z2(J))
650  LF(J) = Z3(J)
660 WOL(J) = W/(LF(J))
670  NEXT J
680  LPRINT"********************"
690 FOR J = 1 TO 25
700 LPRINTJ, RAD(J), LF(J), WOL(J)
710  NEXT J
720  LPRINT"********************"
730  FOR J = 1 TO 21
740 IR(J) = (I(J)*W)/(Q*UP*A*NA)
750  NEXT J
760  FOR J = 1 TO 21
770  LPRINT J, I(J), IR(J)
780  NEXT J
790  LPRINT"*******************"
800  END
```

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