CHARACTERISTICS OF A TUNNEL DIODE

OPERATING IN A NUCLEAR REACTOR

by

Leonard Robert Fleischer

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Signatures have been redacted for privacy

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I. INTRODUCTION

In 1958, by investigating semiconductors doped to saturation, Japanese physicist Dr. Leo Esaki developed the Esaki, or "tunnel" diode. This device has caused a great deal of excitement in the electronics industry. In the year and a half since the tunnel diode was first reported, manufacturers of semiconductor devices have developed tunnel diodes from the laboratory stage through the pilot plant stage to the verge of full scale production.

The reasons for the great interest in and rapid development of tunnel diodes lie, as one would expect, in the unusual electronic properties of the device. Because they are so heavily doped, tunnel diodes are much less sensitive to the perfection of their crystal structure and surface effects than other semiconductor devices. Therefore, the characteristics of tunnel diodes are stable over a large range of temperatures, are able to operate in a wide variety of critical environments, and are reported to be relatively insensitive to nuclear radiation. Also, tunnel diodes are structurally simple, small, and light weight; have low power supply requirements and low noise levels; and are capable of operating at very high frequencies, on the order of kilomegacycles.

What makes tunnel diodes unusual is the fact that as the forward voltage, or bias, across the diode is increased, the current flowing through the diode increases to a maximum, decreases to a low, flat minimum, and then increases again as an ordinary diode would. In the region in which the current decreases as the voltage increases the diode has, in effect, a negative resistance. It is that negative resistance that allows the tunnel diode to be used as an amplifier, a high frequency oscillator, or a high speed switch.

In the nuclear field, tunnel diodes are apparently admirably suited for use as high speed switches in control systems, as amplifiers and oscillators in instrumentation systems, and in a variety of applications in computers used in conjunction with nuclear devices. Probably the most important of the latter systems would be in connection with nuclear powered aircraft and nuclear weapons systems where the additional advantage of a high potential for use in microminiaturized electronic equipment, because of inherent stability and low power dissipation, would be a prime incentive for the use of tunnel diodes. (2, 9, 10, 11, 14, 15, 16, 18, 19, 20)

A tunnel diode is a p-n junction with an electrode connected to each region. The two requirements on the p-n junction that differentiate tunnel diodes from other p-n diodes are (1) that the junction be narrow (the chemical transition from n-type to p-type must be abrupt), on the order of one hundred Angstrom units in thickness, and (2) that the impurity concentrations be high enough that both regions be degenerate (that is, the electrons fill the lowest available energy levels), on the order of 10^{19} atoms per cubic centimeter.

The current at low voltages is carried by electrons which traverse the p-n barrier by quantum mechanical tunneling. This phenomenon may be looked at as the disappearance of an electron on one side of the barrier and its simultaneous appearance on the other side, as if it tunneled through a barrier it could not go over. It is required that there be an unoccupied, allowed state on the other side of the barrier for the electron to go into, explaining the need for degeneracy. For the tunneling probability to be high, it is necessary that the barrier be narrow (14).

A schematic representation of electron flow as a function of bias is shown in Figure I (16, 20). In (a), with no voltage difference between the n and p regions, the Fermi level of both regions is the same, the tunneling of electrons is equal in both directions, and the net current is zero.

With a small forward bias, as illustrated in (b), the band gap is increased until there are more empty states available in the p-type region than in the n-type region. Therefore, the electron flow from the n-type region to the p-type region is greater than that from p-type region to the n-type region resulting in a net forward current.

As the bias is increased further, the band gap increases so that the energy levels of most of the electrons in the n-type region are higher than those of the unoccupied states in the p-type region, as shown in (c). If the bias is increased still further, the band gap increases until the edge of the conduction band is at a higher energy that the edge of the valence band, as in (d). Theoretically, the current should fall to zero in this region, but, in actuality it falls only to some intermediate minimum level which is called, because its origin is not understood, "excess current" (14).

Upon still further increase in bias, the conduction electrons are

Figure I. Band theory diagrams of electron flow as a function of bias across a tunnel diode

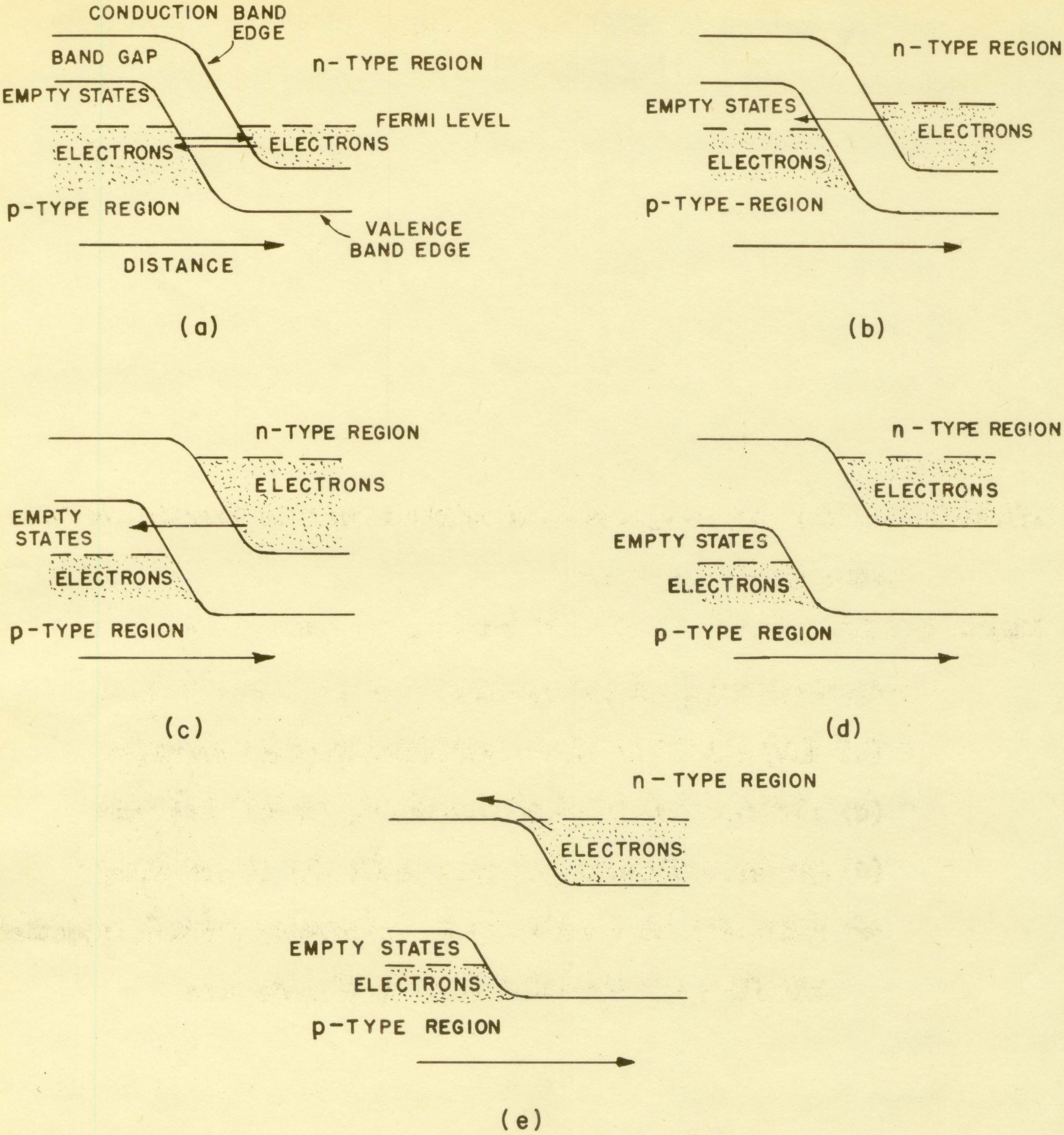
(a) zero bias, no net current

(b) slight forward bias, increasing forward current

(c) greater forward bias, decreasing forward current

(d) greater forward bias, no current due to tunneling

(e) still greater forward bias, increasing forward injection current as in "conventional" semiconductors


CONDUCTION BAND EDGE
BAND GAP
n-TYPE REGION
EMPTY STATES
FERMI LEVEL
ELECTRONS
ELECTRONS
p-TYPE REGION
VALENCE BAND EDGE
DISTANCE
(a)
n-TYPE REGION
EMPTY STATES
ELECTRONS
ELECTRONS
p-TYPE-REGION
(b)
n-TYPE REGION
ELECTRONS
EMPTY STATES
ELECTRONS
p-TYPE REGION
(c)
n-TYPE REGION
ELECTRONS
EMPTY STATES
ELECTRONS
p-TYPE REGION
(d)
n-TYPE REGION
ELECTRONS
EMPTY STATES
ELECTRONS
p-TYPE REGION
(e)

energetically promoted until they are able to go over the barrier as in heretofore "conventional" semiconductors, as in (e), and from this point, the current increases almost exponentially with increasing voltage.

This variation of current with voltage is illustrated in Figure II as a curve termed the I-V (current-voltage) characteristic. The lower case letters labeling the curve correspond to the conditions illustrated in Figure I.

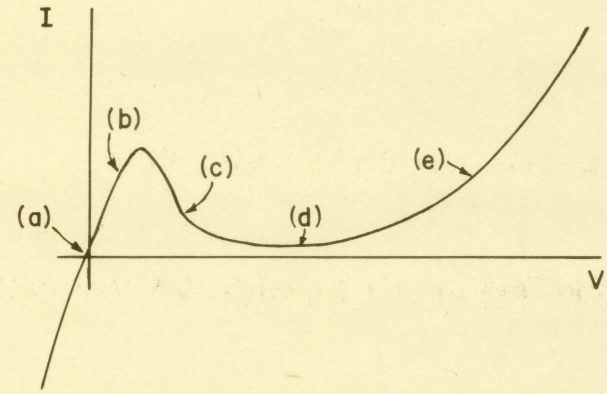
The successful utilization of tunnel diodes where they might be exposed to nuclear radiation depends upon whether or not the radiation will change the electronic characteristics of the diode. Experiments have shown that it requires a great deal of damage ($\sim 10^{15} - 10^{16}$ nvt) to put a tunnel diode out of commision. That is, tunnel diodes are about ten times less susceptible to permanent radiation damage than transistors (9, 11, 18).

One of the unexplained phenomena regarding the operation of tunnel diodes was that tunneling occurred with equal facility in materials with direct band gaps and in materials with indirect band gaps. In an indirect band gap the maximum energy in the valence band occurs at a different value of momentum than the minimum energy in the conduction band. Therefore, a tunneling electron would have to change its momentum in the process, which would violate the classical conservation laws.

Then, another unexplained phenomenon, "wiggles" in the I-V characteristic of silicon tunnel diodes at liquid helium temperatures

Figure II. I-V characteristic of a tunnel diode

(The lower case letters correspond to the conditions illustrated in Figure I.)


I
(b)
(c)
(a)
(d)
(e)
V

was suggested as related to the momentum change. Further experiments showed that the two phenomena were indeed related. The "wiggles" correspond to tunneling processes assisted by ultrasonic lattice vibrations. Measurements showed these vibrations, or phonons, have the right frequency for momentum conservation (20).

The experiments investigating radiation damage in semiconductors have been, for the most part, measurements of the characteristics of the samples before and after irradiation, exposing different samples for different flux times. However, it seems not unlikely that while exposure to radiation might not harm semiconductors, operating characteristics might differ depending on whether or not the samples were operating in a radiation field, and might differ as a function of the intensity of the radiation. This possibility seems especially likely for tunnel diodes since it is known that the tunneling process is affected by lattic vibrations.

It is the purpose of this investigation to look for changes in the characteristics of tunnel diodes operating in a nuclear reactor, and for transients in the behavior of the diodes corresponding to reactor transients.

II. RADIATION DAMAGE IN SEMICONDUCTORS

Experiments show three types of changes in semiconductor crystals as a result of irradiation: Transient; permanent, removable; and permanent, unremovable. The first type of damage results from the passage of a charged particle through the crystal leaving electron-hole pairs in its wake. These electron-hole pairs are able to diffuse through the crystal and annihilate one another in the order of three microseconds. The energy thus released shows up as localized temperature increases.

Permanent, removable damage is lattice dislocations and distortions caused by elastic collisions with fast, heavy particles such as fast neutrons or alpha particles. The lattice imperfections result in electron and hole traps, the electron traps predominating, as well as acting as scattering centers, all of which tends to decrease the conductivity of the crystal. This type of damage can be removed by annealing the crystal. Indeed, annealing takes place in the crystal at all temperatures above absolute zero, the degree of the annealing increasing with temperature, thus partially removing the damage even as it is formed. For this reason radiation damage in semiconductor crystals decreases with increasing temperature. However, the self-annealing effect is rather small at reasonable operating temperatures, and the times necessary for complete or nearly complete removal of the damage at these temperatures would be unreasonably large.

Permanent, unremovable damage is interstitial and replacement impurities caused by the nuclear transmutations resulting from neutron capture and the subsequent decay of the excited nucleus. Electrons or holes are added to the crystal depending on the atomic number of the impurity nucleus. The result is a substitutional alloy having the same properties as if the impurities were introduced chemically. Indeed, this method has been suggested as a controlled means of doping semiconductors. In fact, one of the observations in radiation damage experiments is that n-type semiconductor material has been changed to p-type material (and vice-versa) by nuclear transmutations. This type of damage is not removable except by metallurgical refining (13).

The basic electronic properties of "conventional" semiconductor devices are not appreciably changed by irradiation until integrated neutron fluxes of the order of 10^{11} neutrons/cm.^{2} for transistors and 10^{13} neutrons/cm.^{2} for diodes are achieved. To completely destroy the characteristics of a semiconductor device requires integrated fluxes on the order of 10^{15} neutrons/cm.^{2} for transistors and 10^{16} neutrons/cm.^{2} for diodes. The principal effects of irradiation on the characteristics of diodes are increasing forward resistivity, decreasing backward resistivity, decreasing switching time, and increasing noise levels with increasing integrated flux (1, 4, 7, 12).

The radiation used in the experiments leading to this summary of data was predominantly fast and epithermal neutrons. To date, there are apparently no published data available on the effects of thermal neutrons on semiconductor devices. However, it has been estimated on the basis of what data are available that the damage caused by a fast neutron flux would be approximately equivalent to the damage caused by a thermal neutron flux greater than the fast flux by a factor of ten (12).

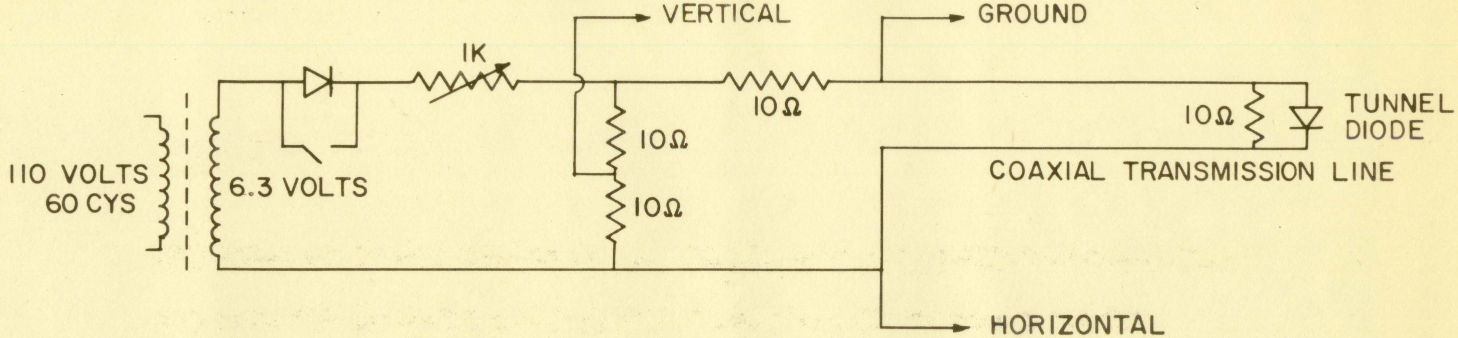
III. EXPERIMENTAL METHOD

This investigation was planned to irradiate tunnel diodes while they were operating as part of a circuit. The facility used for the irradiation was the equipment test chamber of the UTR-10 reactor at Iowa State University. The bottom of the chamber is on a level with the top of the reactor core, and separated from it by three feet of graphite and a lead gamma-ray curtain. Therefore, the radiation reaching the tunnel diodes in the equipment test chamber was essentially thermal neutrons only.

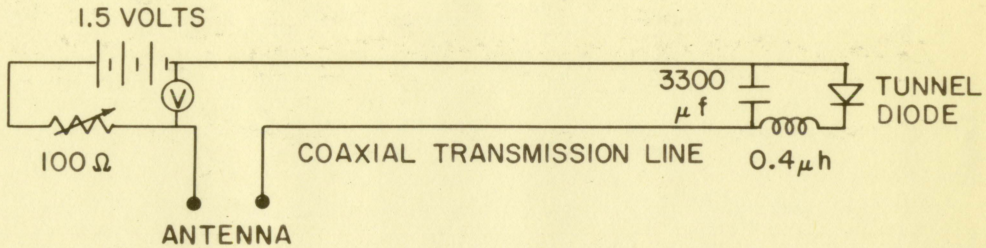
Two circuits were chosen: One to trace the I-V characteristic of the tunnel diode on an oscilloscope, the other to use the tunnel diode as an oscillator so that its resonant frequency, and hence its capacitance, could be measured. The measurements were made at different flux levels, and while the reactor was in a transient state.

The circuits used are shown in Figure III; (a) is the circuit for tracing the I-V characteristic on a Hewlett-Packard oscilloscope, (b) is the circuit used for setting the diode into oscillation and broadcasting its signal. The trace on the oscilloscope was recorded by photography. The frequency of the oscillations was measured with a Gertsch Frequency Meter.

Difficulties were encountered because it was necessary to keep the detection equipment outside the reactor, while the tunnel diodes were inside the reactor. The problems of using a long transmission line in the circuit were solved by Dr. Robert Sharpe of the Iowa State University Department of Electrical Engineering.


VERTICAL
GROUND
1K
10Ω
10Ω
10Ω
10Ω
10Ω
TUNNEL DIODE
110 VOLTS
60 CYS
6.3 VOLTS
COAXIAL TRANSMISSION LINE
HORIZONTAL

(a)


1.5 VOLTS
V
3300 μf
TUNNEL DIODE
100 Ω
COAXIAL TRANSMISSION LINE
0.4μh
ANTENNA

(b)

The tunnel diodes used were development models provided by the Semiconductor Division of Raytheon Company, Needham Heights, Massachusetts. They are made of germanium, heavily doped ($\sim 10^{19}$ impurity atoms/cm^3) with arsenic.

IV. RESULTS

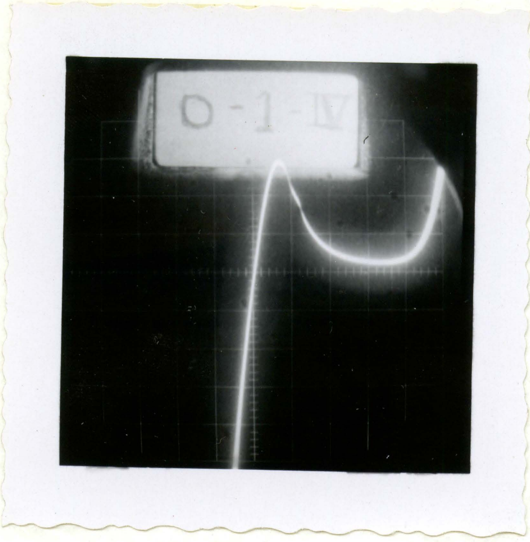
Data were taken for flux values at the diode between 1.8×10^3 and 1.9×10^5 neutrons/cm^2-sec., and for integrated fluxes between 0 and 1.5×10^{10} neutrons/cm^2 . All of the photographs of the I-V characteristic of the same tunnel diode are the same as the I-V characteristic of the diode before irradiation.

Pictures were taken over the same range of flux as the reactor power was dropped to near zero and again as the power was increased to give the maximum flux used, both times the photographs being multiple exposures of a single negative. The resultant picture of the oscilloscope trace of the I-V characteristic is the same as any of the other photographs of the characteristic of the same diode. Except for the effects of greater exposure of the emulsion, there is no broadening or motion of the trace in the picture. Figure IV is several photographs of the I-V characteristic under different conditions of reactor operation, taken from the oscilloscope.

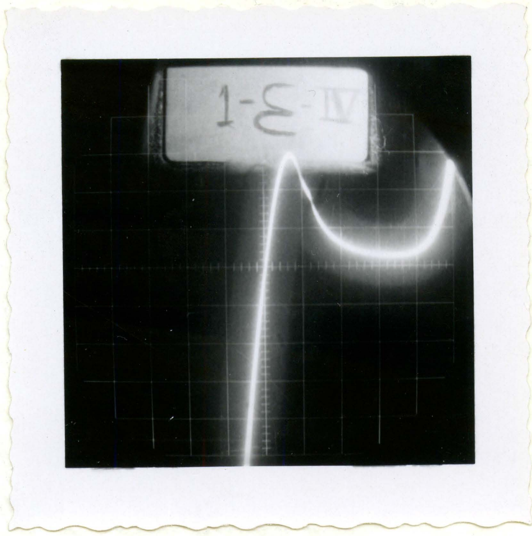
The capacitance measurements made are of dubious validity. Because of the weak signal strength of the test circuit and the strength of local interference, there is no certainty that the diode's oscillations were picked up at all. Furthermore, only one run to gather this data was made because of the failure of one of the diodes. It is presumed that the failure of the diode was not caused by radiation damage, because another diode subjected to the same conditions at the same time was apparently not affected. The supplier of the diodes, Raytheon Company, stated that, "...these (the tunnel diodes)

Figure IV. Photographs of the oscilloscope trace of the I-V characteristic for several flux levels

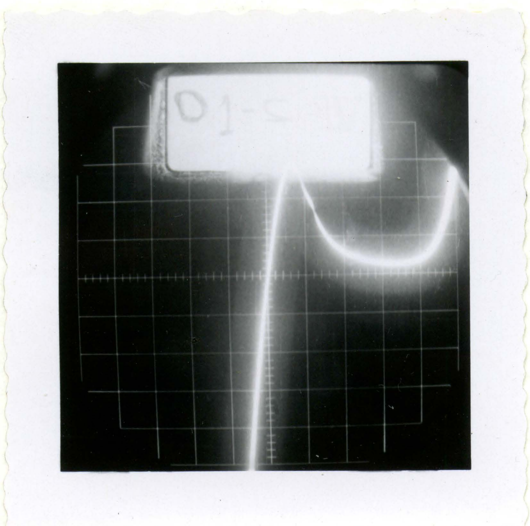
(a) 0 neutrons/cm.^{2}-sec., (b) 1.85 x 10^3 neutrons/cm.^{2}-sec.,
(c) 1.85 x 10^4 neutrons/cm.^{2}-sec., (d) 9.1 x 10^4 neutrons/cm.^{2}-sec.



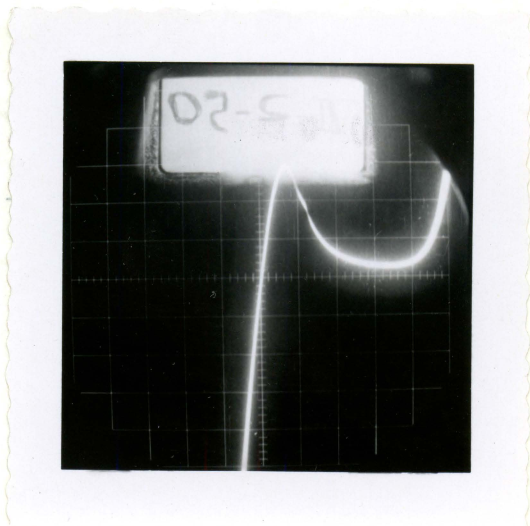
(a)



(b)



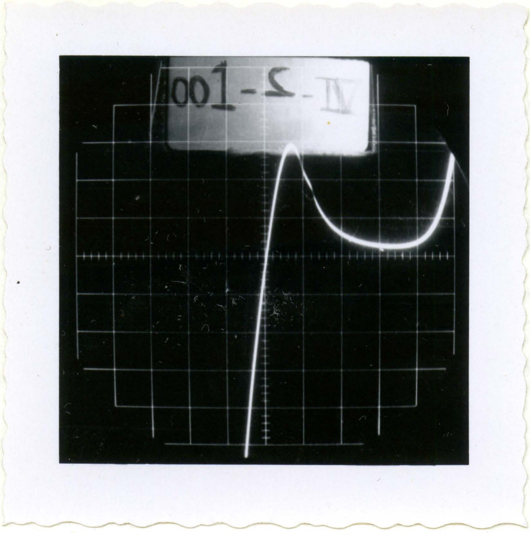
(c)



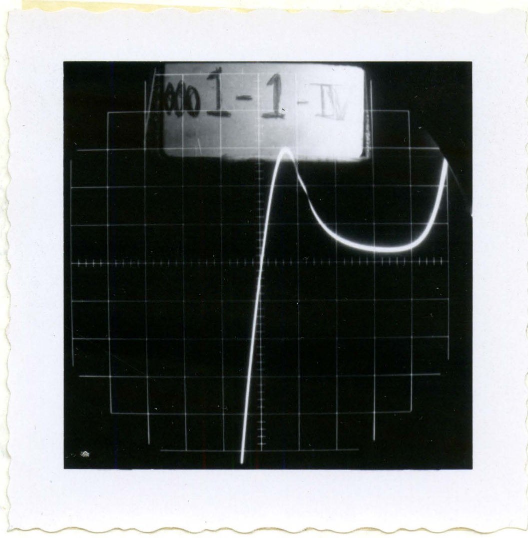
(d)

Figure IV. (Continued)

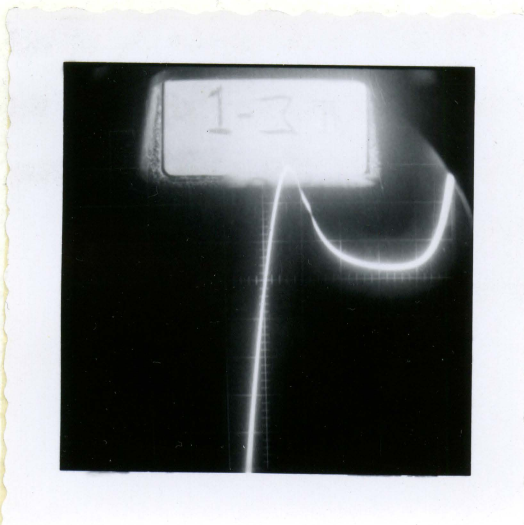
(e) 1.85×10^5 neutrons/cm.^{2}-sec., (f) 1.85×10^6 neutrons/cm.^{2}-sec., (g) a multiple exposure at the preceeding five flux levels as the reactor power dropped from 1 kw to 0.1 watt on a shim rod scram, (h) a multiple exposure at the same five power levels as the reactor power was raised continuously from 0.1 watt to 1 kw.



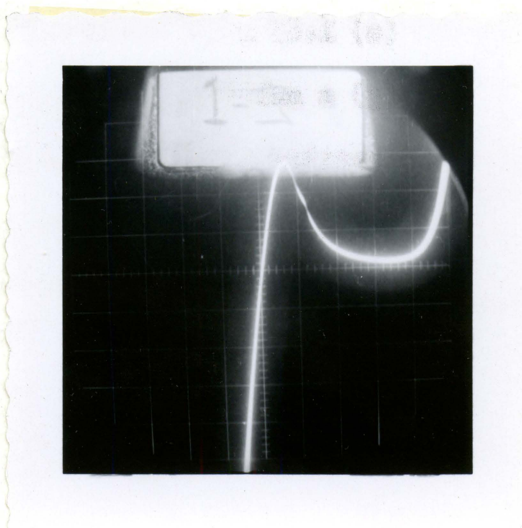
(e)



(f)



(g)



(h)

are developmental units and probably not as stable as they should be .."

However, there was an apparent small frequency change as the flux level at the diode changed. The frequency varied from 37.26 mc at 0 flux and 0 integrated flux to 36.115 mc at a flux level of 1.85×10^6 neutrons/cm.^{2}-sec. and an integrated flux of 4.6×10^7 neutrons/cm.^{2} One more measurement gave a frequency of 36.00 mc at a flux level of 1.85×10^6 neutrons/cm.^{2}-sec. and an integrated flux of 8.9×10^9 neutrons/cm.^{2}, after which it became necessary to abandon the test in favor of staying with the I-V characteristic. It should be pointed out that a primary factor in the choice between the two test circuits was the doubt in the validity of the frequency measurements.

The change in frequency over the course of the experiment is only 3.48%, which could concievably be due to a slight decrease in the voltage source (a dry-cell battery) which might not show up on the voltmeter which was much less precise than the frequency meter. The frequency is related to the capacitance of the diode by $\omega = 2\pi f = (LC)^{-\frac{1}{2}}$, where L is the tuned inductance of the circuit (0.4 μh) and C is the capacitance of the diode. Therefore, the capacitance varies from 45.6 $\mu\mu$f to 48.8 $\mu\mu$f, a change of 6.55%. The frequency changes as a function of integrated flux and flux level during measurement are listed in Table 1.

It is estimated that if the measurements had been continued until the maximum integrated flux of 1.5×10^{10} neutrons/cm.^{2} had been achieved, the deviation of the capacitance would not have exceeded 10%, if indeed the deviations noted were caused by the radiation.

Table 1. Frequency changes in the output of a tunnel diode acting as an oscillator with increasing integrated flux and flux level

Integrated flux, neutrons/cm.^{2}-sec.	Flux level neutrons/cm.^{2}-sec.	Frequency megacycles/sec.
0	0	32.26
7.76×10^5	1.85×10^3	36.89
6.33×10^6	1.85×10^4	36.80
1.71×10^7	3.6×10^4	36.72
3.9×10^7	9.1×10^4	36.46
6.36×10^7	1.37×10^5	36.35
1.19×10^8	1.85×10^5	36.23
4.42×10^8	1.85×10^6	36.12
8.55×10^9	1.85×10^6	36.00

V. CONCLUSIONS

The results of this study indicate that, on the basis of the data collected herein, tunnel diodes are suitable for use in nuclear applications, without fear of transient property changes, if they are not exposed to radiation fields greater than 1.85×10^6 thermal neutrons/cm.^{2}-sec. Other investigations measuring residual changes in electronic characteristics as a function of integrated flux indicate that the use of tunnel diodes in nuclear fields would not be restricted by integrated fluxes less than 10^{15} neutrons/cm.^{2}

This investigation was limited by time, forthcoming modifications to the reactor core which restricted the maximum allowable flux levels, and local radio interference. It is suggested that the results and conclusions presented herein could be advantageously checked and extended under more suitable conditions at a later date.

There is no published account of previous measurements of the characteristics of operating circuit components in a nuclear flux. Placing an experimental portion of an operating circuit in a nuclear reactor while maintaining circuit integrity and operation is a new extension of the techniques of radiation damage investigation. Although the data of this study are not comprehensive, they are unique.

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VII. APPENDIX. CALIBRATION OF FLUX IN THE EQUIPMENT TEST CHAMBER WITH INDICATED REACTOR POWER

The flux in the equipment test chamber was calibrated with the reactor power indicated at the console by indium foil activation. In these calculations it was assumed that the indium was all In^{115} (it is actually 95.77% In^{115}), and that after the period between activation and counting, the secondary mode of decay, with a half life of 13 seconds, was negligible.

The rate of buildup of In^{116} atoms can be expressed by

$$\frac{dN_{116}}{dt} = N_{115}\,\sigma_{115}\,\phi - N_{116}\,\lambda_{116} \quad \text{where}$$

N = no. of atoms present

σ = cross section, in cm^2.

ϕ = flux, in neutrons/cm^2-sec.

λ = decay constant, in inverse time

t = time irradiated

multiplying both sides of the equation by $e^{\lambda_{116}t}\,dt$ gives

$$dN_{116}e^{\lambda_{116}t} + N_{116}\,\lambda_{116}\,e^{\lambda_{116}t}\,dt = N_{115}\,\sigma_{115}\,\phi\,e^{\lambda_{116}t}\,dt,$$

and integrating,

$$N_{116}\,e^{\lambda_{116}t} = N_{115}\,\sigma_{115}\,\phi\,e^{\lambda_{116}t}/\lambda_{116} + C.$$

If it is assumed that $N_{115} = N^{\circ}_{115}$ at time $t = 0$ and does not change appreciably in the course of irradiation, then

$$C = -N^{\circ}_{115}\,\sigma_{115}\,\phi$$

and $N_{116} = (N^{\circ}_{115}\,\sigma_{115}\,\phi/\lambda_{116})(1 - e^{-\lambda_{116}t})$.

The activity of the irradiated indium is given by,

$$D \equiv N_{116}\,\lambda_{116} = N^{\circ}_{115}\,\sigma_{115}\,\phi\,(1 - e^{-\lambda_{116}t}).$$

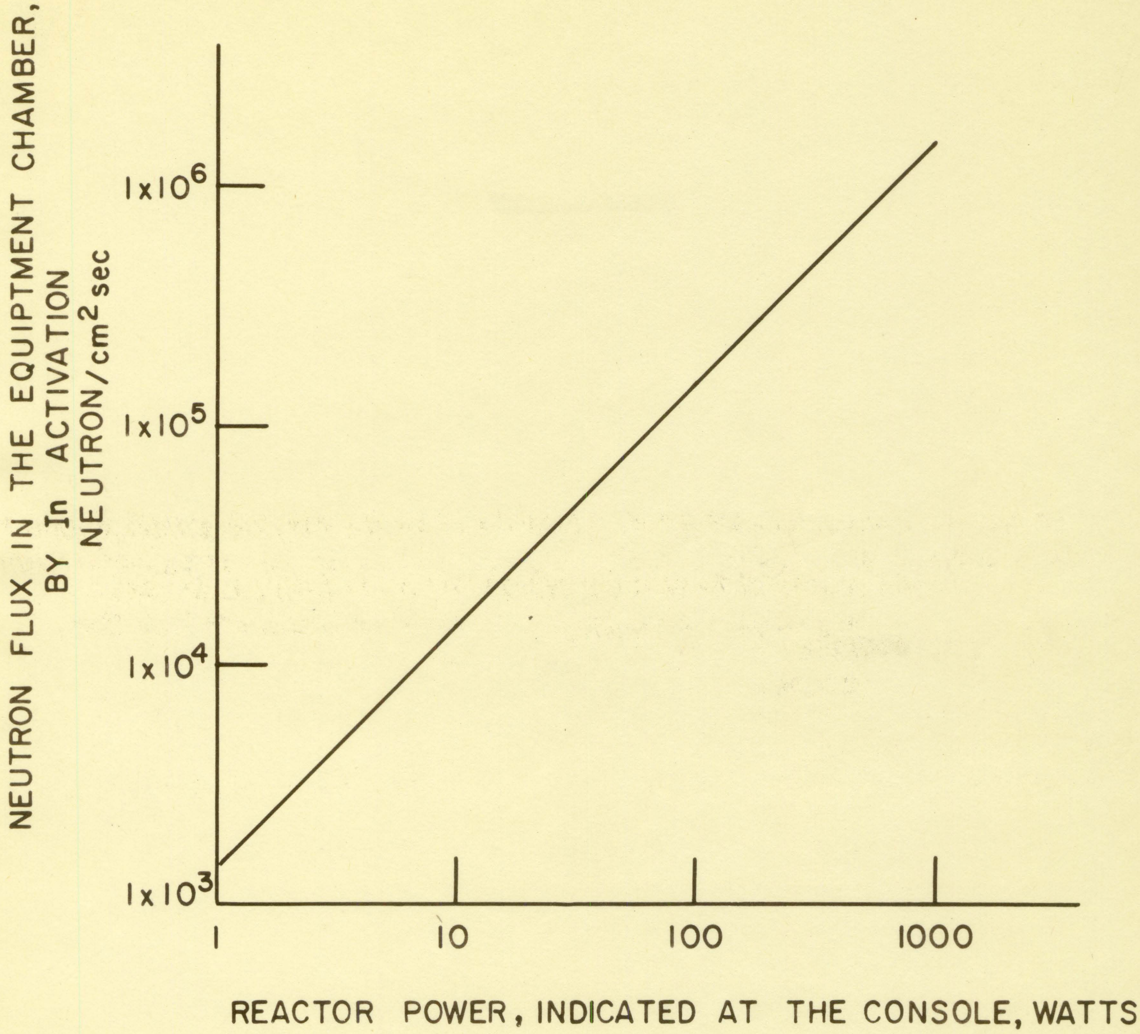
Therefore,

$$\phi = D/N^{\circ}_{115}\,\sigma_{115}\,(1 - e^{-\lambda_{116}t}).$$

D is found by correcting the counting rate of the foil sample for counter dead time, geometry, efficiency, and back scattering, as well as correcting for decay in the time between the removal of the foil from the flux and the time of counting.

Figure V is a calibration plot of the logarithm of flux, determined by indium activation, versus the logarithm of reactor power, indicated at the console.

Figure V. Calibration curve: Neutron flux in the equipment chamber as a function of reactor power as indicated at the console


NEUTRON FLUX IN THE EQUIPTMENT CHAMBER,
BY In ACTIVATION
NEUTRON/cm² sec
1x10⁶
1x10⁵
1x10⁴
1x10³
1
10
100
1000
REACTOR POWER, INDICATED AT THE CONSOLE, WATTS