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ELECTRON-VOLTAIC CELL STUDY

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A. Semiconductor Materials

1. Characteristics and Properties of Gallium Arsenide.

Gallium arsenide is a A^{III}-B^V intermetallic semiconductor. The crystal is dark gray with a metallic sheen. It has the zinc-blende structure which is identical to the diamond lattice, except that alternate sites are occupied by gallium and arsenic atoms. This dual occupancy is responsible for many of gallium arsenide's unique properties.

The diamond crystal structure requires that each atom have four valence electrons and form four covalent bonds with its neighbors. This gives each atom the use of eight valence electrons, the required number to form filled outer shells.

Examinations of the periodic table shows that a gallium atom has three, and an arsenic atom five, valence electrons. Each atom has an outer shell capacity of eight electrons. To form a zinc-blende type crystal the arsenic atom has to loan one of its valence electrons to the gallium so that each may have four to use in producing a tetrahedral structure, like the group IV elements. The resulting crystal is predominately covalent, however, because of the electro-negative difference between the two elements a small additional ionic component is introduced into the bonding. This ionic component increases the amount of energy lost by the valence electrons in the formation of the crystal. The lower energy level of the crystal means an increase in binding strength. This is reflected in the larger forbidden energy gap that GaAs has over its group IV counterpart, Germanium. The energy gap relation is given by:

$$E_g(\text{ev}) = 1.53 + 9.4 \times 10^{-6}P(\text{atm}) - 4.9 \times 10^{-4} \text{ } ^\circ\text{K} \quad (1)$$

which is about 1.35 ev at room temperature. (1)

The charge difference between gallium and arsenic introduces a second difference from group IV crystals--polarization of valence and inner electrons towards the arsenic atoms.

One relationship which is used to compare the degree of polarization between various A^{III}-B^V compounds is given by: (2)

$$J = \frac{E_{\text{ionic}}}{E_{\text{covalent}}} (Z^{\text{III}} + Z^{\text{V}})^{3/2} \quad (2)$$

J = polarization in arbitrary units

E_{ionic} = extra ionic energy due to electro-negative difference of components.

E_{covalent} = covalent binding energy.

Z^{III} and

Z^{V} = atomic numbers of the A^{III} and B^{V} elements respectively.

Polarization explains the reason for the low hole mobility found in gallium arsenide. In the diamond lattice the valence electrons are normally symmetrically distributed over valence bridges. A hole is created if an electron is missing. If an electron from any of the six neighboring valence bridges jumps into the hole, the hole is considered to have moved. An electron from any of the six neighboring valence bridges has the same probability of doing this.

In the GaAs lattice, with its attendant polarization, this movement of holes is altered somewhat. The valence electrons are not distributed symmetrically around the elements but have moved closer to the arsenic atoms. So, a hole now has three valence bridge neighbors which are closer and three which are farther away. In the first group the jump probability has increased while in the more distant bonds the probability has decreased. Hole movement through the lattice depends upon the participation of the second group which in turn lowers the hole mobility. This is equivalent to an increase in the effective hole mass.

One factor contributing to the increased electron mobilities is the higher binding energy. This is favorable to a smaller amplitude of lattice oscillations and therefore smaller lattice scattering of mobile charge carriers. (3)

"Pauling has suggested that the covalent-bond energy between two equally shared electrons at the minimum bond distance is related to the reciprocal of the bond length." (4) This suggests that there should be some relationship between the forbidden energy gaps of group IV semiconductors, and AIII-BV intermetallic compounds. Figure 1 shows that the energy gaps are proportional to $1/a^2$ where a is the lattice parameter. Of particular interest is the relationship of GaAs and Ge since they have virtually the same lattice constant. This same $1/a^2$ relationship can be extended to show the relative difference in melting points. (See Figure 2.)

An electron-hole pair in gallium arsenide has the ability to combine directly across the energy gap without momentum transfer to or from the lattice. The energy that the pair possesses is radiated as infrared light. The ability to

combine directly has important effects on the minority carrier lifetime. The rate of recombination R is proportional to the product of the hole density p and the electron density n .

$$R = \alpha pn \quad (3)$$

α for GaAs is $1.4 \times 10^{-10} \text{ cm}^3/\text{sec}$. In n-type material the lifetime τ is defined in terms of the recombination rate as $R = p/\tau$. From these two equations one can obtain the lifetime as $\tau = 1/\alpha n = 10^{10}/1.4 n$. For material doped to $10^{18}/\text{cm}^3$, $\tau \approx 10^{-8} \text{ sec}$. A highly purified material will reduce the number of traps, but will not affect the lifetime directly. As can be seen above, lifetime is determined by the density of the majority carrier.

The general problem of doping is much more complex in GaAs than in group IV semiconductors. A perfect GaAs crystal has an electronically closed structure. The electronic bonds do not contribute to the electrical conductivity even though the atoms in the lattice are not chemically identical. Electrical conduction results when the insulating electron bonds are broken either by thermal excitation or as a result of an incorporated defect which alters the combining proportions of the electrons. This can occur in growing the crystal. An excess of gallium can lead to p-type conduction, whereas an excess of arsenic leads to n-type conduction. Methods of detecting these minute deviations from stoichiometry have only recently been developed. (8) Intentionally added column II elements such as zinc and cadmium act as acceptors when substituted on gallium sites. Column III elements are neutral on gallium sites but act as acceptors on arsenic sites. Column IV elements, such as germanium, are donors on gallium sites; acceptors on arsenic sites; neutral when they enter the lattice in pairs, replacing a gallium and an arsenic atom. Column VI elements, such as selenium, act as donors on arsenic sites.

Interstitial impurities can have a variety of values depending on the type of impurity and its location in the crystal. Some typical values for impurities are: (3)

Cu	acceptor	0.14-0.16 ev
Mn	acceptor	0.1 ev
Au	acceptor	0.31 ev
Zn	acceptor	0.014 ev
Cd	acceptor	0.020 ev
Fe	acceptor	.37 ev
Si	donor	.005 ev
Ag	acceptor	----
Mg	acceptor	----

Ca	acceptor	----
Ge	donor	----
Sn	donor	----
S	donor	----
Se	donor	----
Te	donor	----

N or p type GaAs is produced by incorporating an impurity which lies close to the conduction or valence bond. A high resistivity material can be made by doping with an impurity which lies deep in the forbidden gap region. (6,7) Oxygen is commonly used to accomplish this. Iron, cobalt, and nickel may also be used.

Gallium arsenide is more radiation resistant than silicon but not as resistant as germanium. When using electrons as the bombarding particles, it requires 236 KEV to dislodge a gallium atom, and 267 KEV to create a lattice defect with the arsenic atoms. This energy level is required to impart the required 9.1 ev to gallium and 9.8 ev to arsenic atoms for formation of Frenkel defects. The energy required of the bombarding particle to create an electron hole pair is 6.3 ev. (27,28)

There are at present four methods of growing GaAs crystals. (8) The first of these is the Czochralski technique. The seed is withdrawn from the melt and is rotated to maintain thermal symmetry and cylindrical geometry. Crystals up to 5" long and 1" in diameter have been grown. Because of the tendency of the melt to lose arsenic, the operation is performed under one atmosphere of arsenic vapor.

The floating zone technique consists of a polycrystalline rod of GaAs which is supported vertically within a quartz tube and is zone melted with a coil operated at radio frequency. The rod is passed slowly through the coil, while arsenic vapor is held in the tube.

The horizontal Bridgman method of crystal growth completely melts an ingot of GaAs in a crucible and then moves the crucible through a temperature gradient so that crystallization starts at one end and progresses through the melt. Since the GaAs expands when frozen this operation is conveniently done in a horizontal boat in an atmosphere of arsenic vapor.

The gradient freeze technique produces crystals by gradual solidification of a molten ingot. Crystallization takes place by movement of a temperature gradient along the ingot. The entire system is stationary.

TABLE I

The Properties of Gallium Arsenide

molecular weight	144.67	(9)
composition by weight	Ga 48.21%	(9)
	As 51.79%	
melting point	1238° C	(9)
hardness	4.5	(9)
lattice constant at 24.7° C	5.641907 x 10 ⁻⁸ cm	(10)
atoms/cc	4.46 x 10 ²²	
density	5.32 gm/cc	(11)
dielectric constant	11.1	(12)
permittivity	.982 x 10 ⁻¹² farads/cm	
gap energy	1.35 ev	(13)
n _i at 300° K	2.81 x 10 ⁷ cm ⁻³	(13)
n _i ² at 300° K	7.90 x 10 ¹⁴ cm ⁻⁶	
ρ at 300° K	5 x 10 ⁷ ohm-cm	(13)
σ at 300° K	2 x 10 ⁻⁸ ohm ⁻¹ -cm ⁻¹	
μ _n at 300° K	4000 cm ² /volt-sec	(13)
μ _p at 300° K	450 cm ² /volt-sec	(13)
μ _L (lattice mobility) at 25° C	12,500 cm ² /volt-sec	(14)
thermal expansion coef.	4.97 x 10 ⁻⁶ ° C	(15)
debye temp. (Θ ₀)	314° K	(16)
index of refraction	3.4	(17)
effective mass of electron (m _e [*])	0.072 m ₀	(18)
effective mass of hole (m _n [*])	0.5 m ₀	(18)
effective ionic charge (q [*])	0.46q	(19)
τ _p = τ _n (typical)	10 ⁻⁸ sec.	

m₀ = rest mass of an electron

q = electron charge

Values in the preceeding table, such as resistivity and mobility, have been selected as fairly representative ones. Many different values have been quoted in the literature. This is undoubtedly due to uncontrollable variations occurring during crystal growing.

2. Properties of Silicon

Silicon is a column IV element which crystallizes in the diamond lattice structure. A perfect silicon crystal, at absolute zero temperature, would have no electrons in the conduction band and no holes in the valence band. At higher temperatures current carriers are present. Some originate in the valence band, some from chemical impurities in the lattice, and some from lattice defects of various types. To raise an electron from the valence to the conduction band, in other words, the act of creating an electron-hole pair, requires energy equal to the energy gap between these bands. The energy gap has been found to depend on temperature according to the relation: (30)

$$E_g = 1.12 - .0003T^5 \quad (4)$$

T = temperature °K.

The energy gap increases when pressure is applied.

Chemical impurities in the lattice may act as donors or acceptors. Acceptors come from column III of the periodic table and donors from column V. Impurity ionization values are as follows: (31)

Acceptor:	B	.045 ev
	Al	.057 ev
	Ga	.065 ev
	In	.165 ev

Donor:	P	.039 ev
	As	.049 ev
	Sb	.039 ev.

Mobility is influenced by two collision mechanisms; impurity atom scattering, and lattice-vibration scattering. The relationship between the two can be symbolized as follows: (31)

$$\frac{1}{\mu} = \frac{1}{\mu_L} + \frac{1}{\mu_i} \quad (5)$$

μ_L = lattice mobility

μ_i = impurity atom mobility.

The impurity mobility is: (30)

$$\mu_i = 4.7 \times 10^{17} \left(\frac{m}{m^*} \right)^{1/2} \frac{T^{1/2}}{N_i (1 + 4.5 \times 10^8 T^2 / N_e^{2/3})} \quad (6)$$

T = temperature, degrees K

N_i = total density of all ionized impurities

m^* = effective mass of electron or hole.

From this equation it can be seen that the impurity mobility will decrease with impurity concentration, see Figure 7, but increase with temperature as $T^{3/2}$. As the number of impurity atoms increase, the probability of collision becomes greater, making the mobility smaller. As the temperature increases the average velocity of the carriers increases. This increase makes the charge centers less effective and, as a result, increases the mobility. Lattice-scattering mobility is caused by collisions of the carriers with atoms in the lattice. Lattice mobility decreases with temperature, because as the temperature is increased, lattice vibrations increase and so cause more carrier collisions per unit of time.

When an excess of carriers is present in silicon the crystal tends to return to equilibrium by recombination of holes and electrons. Direct recombination lifetime for electrons and holes in intrinsic silicon is 3.7 seconds, as predicted by the relation $\tau = n_i^2 / G(P+N)$. But measured values run from 30 to 500 microseconds. (31) From this large discrepancy it is obvious that some other process is active. Foreign impurities and structural defects have been found to create recombination centers. Recombination occurs when one of the centers captures a free electron and holds it until it captures a free hole. G is the thermal generation rate.

Recombination in silicon is complicated by another type of recombination center, one which is commonly called a trap. Traps differ in the respect that they can capture carriers but cannot be emptied by capturing carriers of the opposite type. A trap is emptied only by releasing the initial carrier. A trap can hold a carrier for a relatively long time before releasing it to recombine at a normal recombination center. (See Figure 8) (32) This creates an apparent long lifetime. At high carrier levels the traps are all filled and their effect is swamped out.

When silicon is irradiated with electrons, struck atoms can be moved out of their lattice position. The resulting vacancy-interstitial pair constitutes a Frenkel defect. To create this defect the electrons must have a threshold energy of 145 KEV. This energy is required to impart the required 12.9 ev minimum energy to the silicon atom for Frenkel defect formation. (33) An electron-hole pair is created for each 3.6 to 4.0 ev of bombarding energy. (34)

TABLE II
Properties of Silicon

atomic No.	14	
atomic wt.	28.08	
lattice constant at 25° C	5.42×10^{-8} Cm	
atoms/cc	5×10^{22}	
density at 25° C	2.33 gm/cc	
dielectric constant (ϵ_r)	11.9	
permittivity	1.04×10^{-2} farads/cm	
gap energy (ev)	1.12	
μ_n at 300° K	$1350 \text{ Cm}^2/\text{volt-sec}$	
μ_p at 300° K	$490 \text{ Cm}^2/\text{volt-sec}$	
μ_{Ln} (lattice mobility-electrons)	$2.1 \times 10^9 \text{ T}^{-25}$	(31)
μ_{Lp} (lattice mobility-holes)	$2.3 \times 10^9 \text{ T}^{-27}$	(31)
D_n (electrons)	$35 \text{ Cm}^2/\text{sec}$	
D_p (holes)	$12.4 \text{ Cm}^2/\text{sec}$	
N_i^2 at 300° K	$4.62 \times 10^{21} \text{ Cm}^{-6}$	
N_i at 300° K	$6.8 \times 10^{10} \text{ Cm}^{-3}$	
ρ at 300° K	$4 \times 10^4 \text{ ohm-Cm}$	
σ at 300° K	$2.5 \times 10^{-5} \text{ ohm}^{-1}\text{-Cm}^{-1}$	
specific heat (0-100° C)	$0.181 \text{ Cal/gm}^\circ\text{-C}$	
thermal conductivity at 25° C	$0.20 \text{ Cal/sec-Cm}^\circ\text{-C}$	(30)
thermal expansion coefficient	$4.2 \times 10^{-6} (\text{ }^\circ\text{C})^{-1}$	(30)
magnetic susceptibility	$-0.13 \times 10^{-6} \text{ CgS}$	(30)
melting point	1420° C	(30)
boiling point	2600° C	(30)
m_n^* (effective electron mass)	$1.08 m_o$	
m_p^* (effective hole mass)	$0.60 m_o$	
volume compressibility	$0.98 \text{ Cm}^2/\text{dyne}$	

3. The Properties of Germanium

One of the best known of all materials is the brittle, grayish-white element germanium. It, like silicon, is a column IV element which exhibits covalent bonding and a diamond-lattice crystal structure.

The energy gap in germanium is somewhat dependent upon temperature and pressure. The gap energy is given in ev by the relationship: (30)

$$E_g = 0.75 - .0001 T^4 \quad (7)$$

$T = \text{degrees kelvin.}$

As with silicon the energy gap increases when pressure is applied.

Mobility is dependent upon both impurity mobility and lattice mobility. For germanium the impurity mobility is given by: (30)

$$\mu_i = 8.5 \times 10^{17} \left(\frac{m}{m^*}\right)^{1/2} \frac{T^{3/2}}{N_i \ln \left(1 + 8.3 \times 10^8 \frac{T^2}{N_i^{2/3}}\right)} \quad (8)$$

The symbols have the same meaning as those given for silicon. Lattice mobility for electrons is:

$$\mu_{Ln} = 4.90 \times 10^7 T^{-1.66} \quad (9)$$

And for holes: $\mu_{Lp} = 1.05 \times 10^9 T^{-2.33} \quad (10)$

In addition to the connecting relationship between μ_i and μ_L given for silicon, the graph (Figure 11) may be used.

Recombination takes place at recombination centers. However, traps are not a problem with germanium, since they are not active above -80°C . The energy of the recombining carriers at a recombination center can be accounted for in the following ways: (a) auger effect mechanism in which a collision of two carriers occurs, one of them recombines at a recombination center, while the other carries away the energy lost by the first one; (b) exciton formation in which an electron-hole pair (exciton) travels until one of them recombines while the other continues to travel with increased

speed; and, (c) phonon emission in which a phonon (heat wave) is emitted when a carrier is captured.

The predicted lifetime for intrinsic germanium, based upon impurity concentration, is 0.39 sec. Measured values vary from 400 to 2000 microseconds. The variation of lifetime with impurity content is given in Figure 12. Lifetimes are made up of two values related by the following expression:

$$\frac{1}{\tau} = \frac{1}{\tau_v} + \frac{1}{\tau_s} \quad (11)$$

τ_v = interior recombination lifetime,

τ_s = surface recombination lifetime.

Interior lifetime is very sensitive to chemical impurities and imperfections in the lattice. Bombardment of the lattice can have drastic effects on the body lifetime. The lifetime for surface recombination depends upon the dimensions of the germanium as well as on the surface properties, since the carriers must diffuse to the surface before they can recombine there. Surface effects are separated out by defining a surface velocity of recombination, S:

$$S = \frac{\text{number of recombining carriers/sec/unit of surface area}}{\text{excess density of carriers at the surface}}, \quad (12)$$

then $\frac{1}{\tau_s} = S\left(\frac{1}{B} + \frac{1}{C}\right)$ for small values of S, and B and C are the side dimensions of a rectangular crystal. For properly etched germanium surfaces, S has been found as low as 100 cm/sec. At the other extreme, for sandblasted surfaces, S can be as high as 10^5 cm/sec.

Bombardment of germanium with electrons requires a threshold bombarding energy of 360 KEV to impart the minimum energy of 14.5 ev for Frenkel defect formation. The energy required for pair production is 2.9 ev. (37)

Doping is accomplished by using column III and column V elements. Impurity ionization energies are as follows:

Acceptor:	B	.0104 ev
	Al	.0102 ev
	Ga	.0108 ev
	In	.0112 ev

Donor:	P	.0120 ev
	As	.0127 ev
	Sb	.0097 ev.

TABLE III

Properties of Germanium

atomic No.	32	
atomic wt.	72.6	
lattice constant at 25° C	5.62×10^{-8} Cm	
atoms/cc	4.52×10^{22}	
density at 25° C	5.33 gm/cc	
dielectric constant (ϵ_r)	15.8	
permittivity	1.42×10^{-12} farads/Cm	
gap energy	0.72	
μ_n at 300° K	3900 Cm ² /volt-sec	
μ_p at 300° K	1900 Cm ² /volt-sec	
D_n (electrons)	101 Cm ² /sec	
D_p (holes)	49.3 Cm ² /sec	
N_i^2 at 300° K	6.25×10^{26} Cm ⁻⁶	
N_i at 300° K	2.5×10^{13} Cm ⁻³	
ρ at 300° K	46.3 ohm-Cm	
σ at 300° K	0.0216 ohm ⁻¹ -Cm ⁻¹	
specific heat (0-100° C)	0.074 Cal/gm °C	
thermal conductivity at 25° C	0.14 Cal/sec-Cm- °C	
thermal expansion coefficient	6.1×10^{-6} (°C) ⁻¹	
melting point	937° C	
boiling point	2700° C	(30)
volume compressibility	1.3×10^{-12} Cm ² /dyne	(30)
magnetic susceptibility	-0.12×10^{-6} Cgs	
Debye temperature	290° K	
m_n^* (effective electron mass)	0.55 m_o	
m_p^* (effective hole mass)	0.36 m_o	

B. Radiation Damage

Seitz and Koehler have determined a theoretical expression for the cross section for the displacement of lattice atoms by fast electrons. (41) The expression is

$$\sigma = \frac{\pi b^2}{4} \left[\left(\frac{T_m}{T_d} - 1 \right) - \beta^2 \ln \frac{T_m}{T_d} + \pi \alpha \beta \left\{ 2 \left(\left(\frac{T_m}{T_d} \right)^{1/2} - 1 \right) - \ln \frac{T_m}{T_d} \right\} \right] \quad (13)$$

where

$$T_m = 2147.8 E(E+1.0220)/A \quad (T_m \text{ in ev and } E \text{ in mev})$$

$$T_d = \text{energy to displace an atom in ev}$$

$$b^2 = 0.3177 Z^2 (1-\beta^2)/\beta^4$$

$$\beta = v/c$$

$$\alpha = Z/137$$

$$Z = \text{nuclear charge}$$

$$A = \text{atomic mass}$$

$$c = \text{velocity of light.}$$

The number of displaced atoms will be given by

$$N_d = N_o \phi(E) \sigma(E, T_d), \quad (14)$$

where N_o is the density of atoms and $\phi(E)$ is the electron flux at energy, E . T_d is an adjustable parameter determined from experimental measurements and is the minimum energy that must be transferred to a lattice atom to displace it.

TABLE IV

<u>Substance</u>	<u>T_d (ev)</u>	<u>Electron Energy</u> <u>(kev)</u>
Si	12.9	145 (33)
Ge	14.5	360 (33)
GaAs	(Ga)9.1--9.8(As)	236-267 (27)
GaAs	9.6	260 (42)

Table IV lists the threshold values for radiation damage in silicon, germanium and gallium-arsenide.

Figure 14 is a plot of the calculated cross section for silicon versus electron energy. The shape of the curve near the threshold energy is not the same as the experimental results of Loferski and Rappaport. (33) Similarly Cahn indicates that for large electron energies a T_d of approximately 30ev will compare well with experimental results, while smaller values must be used for lower energies. (43) This difference is probably due to the thermal energy of the lattice atoms either aiding or opposing the electron energy in displacing a particular atom. Also most theoretical calculations assume the lattice atom is held in a potential energy well of depth T_d , with a step boundary. (44) The potential well belonging to a lattice atom will not have a rectangular boundary but will have a sloping boundary.

The minority carrier lifetime is related to the radiation flux as follows:

$$\frac{1}{\tau} = \frac{1}{\tau_0} + N_d \sigma_r v_t f, \quad (15)$$

where

τ = the lifetime

τ_0 = the initial lifetime

σ_r = the minority carrier recombination cross section per defect

v_t = the thermal velocity of minority carriers

f = the occupancy factor of the defect

N_d = the number of defect centers per cubic centimeter (45).

In order to compare theoretical calculations with experimental results, assume that monoenergetic electrons travel half the maximum range and lose energy at a constant rate over that distance. Then

$$N_a(E_0) = \left\{ \iint N_0 \sigma(E(x)) dE dx \right\} \emptyset \quad (15)$$

or using the approximations,

$$N_d(E_o) \approx N_o \left(\frac{\sigma(E_o)}{2} \right) \left(\frac{E_o - E_{th}}{E_o} \right) \frac{R_{max}}{2}, \quad (16)$$

where E_{th} is the threshold electron energy for radiation damage. For example, for 250 Kev electrons, $N_d \approx 5.23 \times 10^{-3} \phi$. Now consider cell No. 7 (p/n), listed in Table I of Baicker and Faughnan (45), with $L_{Bo} = 200 \mu$, $\phi = 1.2 \times 10^{15}$, and $L_{Bf} = 15 \mu$. Bemski (39) gives a value of 8×10^{-13} for the minority carrier capture cross section for electron induced defects in n-type silicon. The thermal velocity will be about 10^7 cm/sec at room temperatures. Using the above values and assuming an occupancy factor (f) of one, the calculated value of $L_{Bf} = 4.97 \mu$. Using a damage cross section curve similar to that measured by Loferski and Rappaport would have given an answer closer to the measured result. Also, the recombination cross section could be in error.

Now consider a similar method for calculating damage due to beta particles. The number of defects per unit of flux for a given energy can be calculated, as above, and then multiplied by the probability of a beta particle at that energy. This product can then be integrated over the beta spectrum to give the defects per beta particle. Let $N(E)$ be the probability of a beta particle between E and $E+dE$, then

$$\frac{N_d}{\phi} \approx \int \left[\int N_o \sigma(E) dE dx \right] N(E) dE. \quad (17)$$

For example, for a Promethium-147 source and a silicon semiconductor,

$$\frac{N_d}{\phi} \approx 2.58 \times 10^{-5}. \quad (18)$$

Thus, electrons with an energy of 250 kev produce defects at a rate about 200 times that of Promethium-147 beta particles.

In discussing radiation damage to solar cells, it is conventional to define a critical flux, ϕ_c , as that required to degrade the conversion efficiency of a solar cell by 25% for a standard solar spectrum. The critical flux of 250 kev electrons for p/n cell No.7 is given as 1.1×10^{15} and is the lowest critical flux for any of the p/n cells listed. Thus the Promethium-147 beta particle critical flux for a p/n cell should be approximately 2.2×10^{17} , which corresponds to one curie per square cm for 69 days.

The electron voltaic effect cells constructed at Sandia in August, 1962 had Pm-147 concentrations of the order of one curie per square cm. However, the exact concentration was not known and may be somewhat lower than one curie per square cm. Table V contains a tabulation of the open circuit voltage and short circuit current for the cells as measured November 26, 1962 and February 5, 1963 and also includes the ratio of the $V_{oc}I_{sc}$ product for February 5 to that for November 26. The ratios are considerably greater than the 0.75 that the above calculations would lead one to expect. This is probably due to a Pm-147 concentration such that the activity is less than one curie per square cm. Also, the activity of the source should decrease about five percent over the period covered by the measurements, thus the output should decrease five percent or more just due to decreased source activity.

TABLE V

Date	No. 1		No. 2		No. 3		No. 4	
	I_{sc} μa	V_{oc} mv	I_{sc} μa	V_{oc} mv	I_{sc} μa	V_{oc} mv	I_{sc} μa	V_{oc} mv
11/26/62	8.2	15.4	12.8	98	20.6	90.4	8.3	20.3
2/ 5/63	7.6	13.2	13.2	82	19.8	80	8.0	17.2
ratio	0.795		0.863		0.855		0.817	

For a n/p cell the minority carrier capture cross section for a defect in the base region is 1.9×10^{-15} . (39) Baicker and Faughnan list a value of 1.7×10^{-10} for $N_d \sigma_{rvt} f/\phi$ for an n/p cell irradiated with 300 kev electrons. (45) Using approximations similar to those used for the p/n cell, one obtains a calculated result of 1.98×10^{-10} . Thus, the calculated result is in good agreement with the experimental result for the n/p cell, leading one to suspect the recombination cross section used for the p/n cell. The 300 kev electrons will produce defects at a rate of about 400 times that of Pm-147. The critical flux for an n/p cell irradiated with 300 kev electrons is given by Baicker and Faughnan as 7×10^{10} . (45) Thus the critical flux for Pm-147 beta particles should be approximately 2.8×10^{19} , which corresponds to one curie per square cm for 24 years.

An n/p silicon electron voltaic battery using a Pm-147 source should exhibit little deterioration in response over a five-to-ten-year battery life. The response of a p/n

silicon cell might not be satisfactory over a five-year period, however, the previous calculations are probably conservative in their estimate of radiation damage. Both germanium and gallium arsenide have damage thresholds greater than maximum energy of Pm-147 and would presumably suffer no radiation damage from a Pm-147 source. However, GaAs cells exhibit a damage rate above the threshold that is more severe than that of silicon. (46,47) For 0.8 Mev electrons and a flux greater than 10^{15} electrons per square cm, silicon cells are superior to GaAs by virtue of their more gradual decrease in power output with increasing flux.

C. Choice of Isotope

For use in an electron-voltaic-effect nuclear battery it would be desirable to use a beta emitting isotope with a half-life of five-to-ten years, a maximum energy equal to the damage threshold for the semiconductor and a low atomic weight. Also, the isotope should be available in curies quantities at a reasonable cost. Beta emitting isotopes are available in a wide range of energies and half-lives, however, none seem to meet the above requirements.

TABLE VI

<u>Isotope</u>	<u>Max. Energy</u> (Kev)	<u>Ave. Energy</u> (Kev)	<u>Half-Life</u> (Years)	<u>Cost</u>	<u>Range</u> mg/cm ²
N _i -63	67	19.1	120	\$15/mc	5.8
S _m -151	75.5	20	96*	**	7.3
P _m -147	225	62	2.5	\$3.25/c	53
K _r -85	660	218	10.27	\$15/c	260
Tl-204	765	244	4.1	\$1/mc	310

* No adopted value given in Nuclear Data Sheets, so this value is the average of the half-lives listed.

** Not listed in the Oak Ridge Catalog.

Table VI contains information on five isotopes. The data for maximum energy and half-life were obtained from Nuclear Data Sheets (48), the cost information came from the Oak Ridge catalog (49) and the range was read from Figure 22 in Siegbahn (50). The average energy was computed using curves developed by Marinelli, Brinckerholt and Hime. (51) The ratio of E_{av}/E_{max} varied from 0.265 for Samarium-151 to 0.33 for Krypton-85. These curves were calculated assuming

linear Fermi-Kurie plots and since Nickel-63, Samarium-151, and Promethium-147 have the necessary linear F-K plots their average energies should be fairly accurate. Krypton-85 and Thallium-204 have spectrum shapes that agree with the theoretical shape for a first forbidden unique transition with a spin change of two units and a parity change. The F-K plots of Krypton-85 and Thallium-204 will be linear if an additional correction factor is used. The average energies calculated assuming linear F-K plots should be of the right order of magnitude for Kr-85 and Th-204.

Evans (52) makes the general statement that the average beta-ray energy is about 0.4 of the maximum energy, however, only light elements with large maximum energies will have a ratio that high. The average energy for Promethium-147 was determined from its energy spectra and a value of 63 Kev obtained, which is about the same as was obtained using the curves Marinelli.

The number of beta-particles penetrating an absorber is given by

$$N = N_0 e^{-\frac{\mu x}{\rho}} \quad (19)$$

where x is in gm/cm^2

and
$$\frac{\mu}{\rho} = 17.0 E^{-1.43}. \quad (20)$$

E is the maximum beta energy measured in mev. (50) Let N_a be the number of isotope atoms per cubic centimeter

then
$$N_a = \frac{\delta \times \text{No. of radioactive atoms per molecule}}{\text{molecular wt.} \times 1.66 \times 10^{-24}}, \quad (21)$$

where δ is the density in grams per cubic centimeter. The number of beta decays per cubic centimeter per second will be

$$I_\beta = \frac{N_a 0.693}{T_{hl}} e^{-\frac{0.693t}{T_{hl}}}, \quad (22)$$

where T_{hl} is the half-life of the isotope. The number of beta-particles per unit area at the surface of a beta source (see Figure 15) will be given by

$$dN = \frac{I_{\beta} r z}{2(r^2 + z^2)^{3/2}} e^{-\frac{\mu \delta \sqrt{r^2 + z^2}}{\rho}} dr dz$$

and

$$N = \frac{I_{\beta} \rho}{4\mu \delta} \left(1 - \int_0^{1/2} 2x e^{-\frac{\mu \delta z}{\rho x}} dx \right) \quad (23)$$

where δ is the density of the source and z is the source thickness in centimeters. The source is assumed infinite in the r direction but of finite thickness in the z direction.

Figure 16 is a plot of Equation 24--

$$\frac{N}{\left(\frac{I_{\beta} \rho}{4\mu} \right)} = 1 - \int_0^{1/2} 2x e^{-\frac{\mu \delta z}{\rho x}} dx, \quad (24)$$

for various values of $\frac{\mu \delta z}{\rho}$.

Information related to Equation 23 is tabulated in Table VII. The maximum activity is computed assuming infinite source thickness, and $t=0$, i.e., $I_{\beta} \rho / 4\mu \delta$. Oxides were used as the source in cases where the isotope would not be available as a pure substance. However, the isotope itself was assumed to be pure except for Krypton which is available as 5% Kr-85 in Krypton gas.

Rappaport, Loferski and Linder considered this problem, however, they made assumptions which lead to larger maximum surface activities, 2.87 curies per square cm for Pm-147, then those given by Equation 23. In their work, they made a one-dimensional problem out of a three-dimensional problem by assuming the beta particles only moved perpendicular to the surface with one half traveling toward the surface and one half away. The results contained in Table VII should be closer to activities obtainable in practice.

Promethium-147 has the best combination of properties and is probably the most suitable for use in a nuclear battery. Only 6.3% of the beta particles will have energies

greater than the 145 Kev₂ damage threshold for silicon. The maximum range of 53mg/cm² gives a maximum penetration of 228 microns in silicon and 100 microns in GaAs and germanium.

TABLE VII

<u>Isotope</u>	<u>Chemical Form</u>	<u>Density (g/cc)</u>	<u>μ/ρ</u>	I_β	<u>Max. Activity (Curies/cm²)</u>
N _i -63	N _i	8.9	7170	1.675x10 ¹³	0.0158
S _m -151	Sm ₂ O ₃	7.43	5050	5.9x10 ¹²	0.0079
P _m -147	Pm ₂ O ₃	7.32	1053	2.27x10 ¹⁴	1.46
K _r -85	Kr	3.708x10 ⁻³	0.106	2.86x10 ⁹	0.183
Tl-204	Tl	11.85	295.5	1.872x10 ¹⁴	4.29

D. Electron-Voltaic Effect

The purpose of this section is to present a theoretical description of a p-n junction cell with an excess of carriers produced by beta particles. The first part of the section will be a general description of p-n junction action and solar cell construction. The second part will contain a derivation of p-n junction cell characteristics. The discussion will generally be related to silicon cells, however, similar statements could be made for gallium-arsenide and germanium cells.

A p-n junction with excess carriers generated by light or beta particles can be represented by the equivalent circuit shown in Figure 17. (54) The excess carriers together with the p-n junction generates the current, I_s . The output of this current generator is divided between the load, R_L , the shunt resistance, R_p , and the forward biased action of the junction. The junction i-v characteristic can be represented by

$$I_j = I_0(e^{\lambda V_j} - 1), \quad (25)$$

where I_j and V_j are the junction current and voltage, I_0 is the reverse saturation current and $\lambda = q/nkT$. T is the temperature in degrees Kelvin and k is the Boltzmann constant. Junction theory based on diffusion of carriers predicts a

value of one for n , however, experimental results using commercial silicon cells give values around two. Usually in solar cell applications, R_s and R_p have a negligible effect on the load current. For the lower current levels attained in electron-voltaic effect operation R_s will be negligible, however, R_p might be of comparable size to the load resistor.

The reverse saturation current can be expressed as follows:

$$I_o \approx \left\{ q p_n \left(\frac{D_p}{\tau_p} \right)^{\frac{1}{2}} + q n_p \left(\frac{D_n}{\tau_n} \right)^{\frac{1}{2}} \right\} \text{area}, \quad (26)$$

where p_n is the concentration of holes in the n-region, n_p is the concentration of electrons in the p-region, τ_p is the hole lifetime, D_p is the hole diffusion constant, τ_n is the electron lifetime and D_n is the electron diffusion constant. (55) A heavily doped p-region in contact with a moderately doped n-region will give a low I_o , i.e., $I_o \approx q p_n (D_p/\tau_p)^{\frac{1}{2}} \times \text{area}$. If R_s and R_p are neglected, the load current can be represented by the following equation:

$$I_L = I_s - I_o (e^{\lambda V} - 1). \quad (27)$$

Setting $I_L = 0$ gives the following open circuit voltage expression,

$$V_{oc} = \frac{1}{\lambda} \ln \left(\frac{I_s}{I_o} + 1 \right), \quad (28)$$

or

$$V_{oc} \approx \frac{1}{\lambda} \ln \left(\frac{J_s}{q p_n \left(\frac{D_p}{\tau_p} \right)^{\frac{1}{2}}} \right). \quad (29)$$

A semiconductor in thermodynamic equilibrium satisfies the following equation:

$$n_n p_n = A T^3 e^{-E_g/kT}, \quad (30)$$

where E_g is the semiconductor gap energy and A is a constant that depends upon the semiconductor material. The resistivity of the n-region will be $\gamma_n \approx 1/qn\mu_n$ or $n_n \approx 1/q\gamma_n\mu_n$.

These expressions can be used in Equation 29 to give

$$V_{oc} = \frac{1}{\lambda} \ln \left(\frac{J_s}{A_q^2 \gamma_n \mu_n T^3} \cdot e^{\frac{E_g}{kT}} \left(\frac{\tau_p}{D_p} \right)^2 \right) \quad (31)$$

The open circuit voltage will be large when the energy gap is large, the resistivity is low, the mobility is low and the lifetime is long.

Silicon solar cells are usually constructed using 0.05 cm. slices of single crystal silicon prepared by the Czochralski method. Grade IV (lowest grade) silicon is used, however, higher grade material does not give superior performance in solar cells. (56) The resistivity of the base material is usually between 0.5 and 3 ohm-cm with 1 ohm-cm being the most common. The concentration of donor impurity atoms for n-type base material will be approximately 5×10^{15} per cubic centimeter. Both conductivity types of silicon can be used for the base material. In order to form a junction, impurity atoms of the opposite conductivity type are diffused into the base material giving a p-type layer on n base material or a n-type layer on a p base material. A p-n junction is formed at a depth where the concentration of the diffused impurity atoms equals the concentration of impurity atoms in the base material. The junction is parallel to the surface and usually from 1 to 2 μ below the surface. The impurity concentration at the surface will be about 10^{20} atoms per cubic centimeter. Under conditions encountered in solar cell construction, the impurity density in the diffused layer follows a complimentary error function curve. (56,57) However, the impurity density may have a more rectangular characteristic than an erfc curve under certain conditions. There is evidence to suggest that the impurity density of zinc diffused into GaAs gives a more abrupt junction as shown in Figure 18. (58) An exponential variation is a reasonable approximation to the error function complement and is easier to deal with analytically, therefore impurity distributions are usually assumed to be exponential. (59) Thus, the number of acceptor impurity atoms diffused into a n-type base material will be expressed as follows:

$$N = N_{so} e^{-bx} \quad (32)$$

where N_{so} is the surface concentration of impurity atoms, x is depth measured from the surface and b is a constant.

In formulating the problem for an analytic solution, a p-layer diffused into a n-type base material will be assumed. A similar approach could be used for development of equations

for a n/p cell. The action of charge carriers in the diffused p-layer will be discussed first.

Changes in electrostatic potential must satisfy Poisson's equation. The net charge per unit volume will be given by

$$Q = q \left[p - n + N_b - N_{so} e^{-bx} \right], \quad (33)$$

where N_b is the donor impurity density in the base material and the last term is the acceptor impurity density. Poisson's equation requires that

$$\frac{d^2 v}{dx^2} = - \frac{dE}{dx} = - \frac{q \left[p - n + N_b - N_{so} e^{-bx} \right]}{\epsilon}, \quad (34)$$

E is the electric field intensity and ϵ is the permittivity of the semiconductor.

The changes in carrier concentration must satisfy a continuity equation, which states that the rate of change of concentration equals the generation rate minus the recombination rate plus the net flow of carriers into the region. The continuity relations can be expressed in equation form as follows:

$$\frac{\partial n}{\partial t} = g - \frac{n-n_p}{\tau_n} + \frac{1}{q} \frac{\partial j_n}{\partial x} \quad (35)$$

and

$$\frac{\partial p}{\partial t} = g - \frac{n-n_p}{\tau_n} - \frac{1}{q} \frac{\partial j_p}{\partial x}, \quad (36)$$

where g is the generation rate, the recombination rate is the excess minority carrier density divided by the minority carrier lifetime, and j_n and j_p are the electron and hole current densities respectively. Under steady-state operation the carrier concentrations will be constant with time, so that $\partial n / \partial t = 0$ and $\partial p / \partial t = 0$.

The motion of charge carriers in the diffused or surface layer is governed by two mechanisms. (1) An electric field

will cause holes to move in the direction of the field and electrons to move in the opposite direction. (2) A carrier density gradient will cause carriers to diffuse in a direction such that they tend to reduce the gradient. The motion of charges constitutes a current which can be expressed as follows:

$$j_n = q \mu_n E n + q D_n \frac{dn}{dx} , \quad (37)$$

and

$$j_p = q \mu_p E p - q D_p \frac{dp}{dx} . \quad (38)$$

The mobility and the diffusion constant are related by the Einstein equation as follows:

$$\mu_n = \frac{q}{kT} D_n \quad \text{and} \quad \mu_p = \frac{q}{kT} D_p . \quad (39)$$

Equations (34) through (38) form a set of five first order differential equations in five unknowns. Equations (37) and (38) are non-linear because of the $E n$ and $E p$ products. Since the impurity density varies with x , the mobility, the diffusion constant and the lifetime will be functions of x . The non-linearity and the variable coefficients make obtaining a general analytical solution difficult, so approximations will be made.

Consider the electric field intensity for zero current density, then

$$E = \frac{D_p}{\mu_p p} \frac{dp}{dx} = - \frac{D_n}{\mu_n n} \frac{dn}{dx} . \quad (40)$$

Assume the electric field intensity is constant, so that $dE/dx=0$, then

$$p \approx N_{so} e^{-bx} , \quad (41)$$

when far enough away from the junction that n and N_b are small compared with p . The electric field intensity will be

$$E = - \frac{D_p}{\mu_p} b = - \frac{b}{a} \quad (42)$$

where

$$a = \frac{\mu_p}{D_p} = \frac{q}{kT} \quad (43)$$

Consider the order of magnitude of diffusion and drift (electric field) currents. For example, let $N_{so}=10^{20}$, $b=9.9 \times 10^4$, $D_p=12.4$ and $q=1.601 \times 10^{-19}$, then

$$\begin{aligned} -q D_p \frac{dp}{dx} &= (1.601 \times 10^{-19})(12.4)(10^{20})(9.9 \times 10^4) e^{-9.9 \times 10^4 x} \\ &= 1.96 \times 10^7 \text{ amps/cm}^2 \end{aligned} \quad (44)$$

at the surface.

The currents due to diffusion and drift will oppose each other and the difference current that flows through the cell will be small compared with either component. Thus, the flow of current should not modify the constant field. With a constant field Equations (35) and (37) can be solved for the minority carrier density; actually it is easier to solve for the excess density, that is, the density above the normal zero current, zero generation density (n_p). The equations become

$$0 = g - \frac{n_e}{\tau_n} + \frac{1}{q} \frac{dj_n}{dx} \quad (44)$$

$$j_n = q D_n a E n_e + q D_n \frac{dn_e}{dx} \quad (45)$$

which can be combined into one equation in n_e to give

$$\frac{d^2 n_e}{dx^2} - b \frac{dn_e}{dx} - \frac{n_e}{D_n \tau_n} = - \frac{g}{D_n}, \quad (46)$$

where D_n has been assumed constant. If τ_n is also assumed constant and $D_n \tau_n$ replaced by L_n^2 , the equation is a second order differential equation with constant coefficients and can be readily solved.

The generation rate can be approximated by dividing the rate of loss of beta particle energy by the energy required to create an electron-hole pair or

$$g = \frac{N_o E_{av}}{\omega} \propto e^{-\alpha x} \quad (48)$$

where N_o is the surface beta particle intensity, E_{av} is the average beta particle energy, ω is the energy to create an electron-hole pair and $\alpha = 17.0 (E_o)^{-1.43}$. The boundary conditions will be

$$j_n(o) = q S_n n_e(o)$$

or

$$n_e'(o) = \left(\frac{S_n}{D_n} + b \right) n_e(o), \quad (49)$$

where S_n is the surface recombination velocity and

$$n_e(t_1) = n_p(e^{av} - 1) \quad (50)$$

where t_1 is the thickness of the diffused layer or $n_e(t_1)$ is the excess concentration at the edge of the junction. (60,61)
Then

$$n_e = A_1 e^{\left(\frac{b}{2} + \sqrt{\left(\frac{b}{2}\right)^2 + \frac{1}{L_n^2}}\right)x} + A_2 e^{\left(\frac{b}{2} - \sqrt{\left(\frac{b}{2}\right)^2 + \frac{1}{L_n^2}}\right)x} + \frac{N_o E_{av} \alpha e^{-\alpha x}}{\omega D_n \left(\frac{1}{L_n^2} - \alpha^2 - \alpha b\right)}, \quad (51)$$

where

$$A_1 = \frac{\left(\frac{S_n}{D_n} + \frac{b}{2} + \sqrt{\left(\frac{b}{2}\right)^2 + \frac{1}{L_n^2}} \right) \left(n_p (e^{aV} - 1) - \frac{N_0 E_{AV} \alpha e^{-\alpha t_1}}{\omega D_n (\frac{1}{L_n^2} - \alpha^2 - \alpha b)} \right) + \frac{(\frac{S_n}{D_n} + b + \alpha) N_0 E_{AV} \alpha}{\omega D_n (\frac{1}{L_n^2} - \alpha^2 - \alpha b)} e^{t_1 (\frac{b}{2} - \sqrt{\left(\frac{b}{2}\right)^2 + \frac{1}{L_n^2}}} }{2 e^{bt_1/2} \left(\left(\frac{S_n}{D_n} + \frac{b}{2} \right) \sinh \sqrt{\left(\frac{b}{2}\right)^2 + \frac{1}{L_n^2}} t_1 + \sqrt{\left(\frac{b}{2}\right)^2 + \frac{1}{L_n^2}} \cosh \sqrt{\left(\frac{b}{2}\right)^2 + \frac{1}{L_n^2}} t_1 \right)}$$

and

$$A_2 = \frac{\left(\sqrt{\left(\frac{b}{2}\right)^2 + \frac{1}{L_n^2}} - \frac{S_n}{D_n} - \frac{b}{2} \right) \left(n_p (e^{aV} - 1) - \frac{N_0 E_{AV} \alpha e^{-\alpha t_1}}{\omega D_n (\frac{1}{L_n^2} - \alpha^2 - \alpha b)} \right) - \frac{(\frac{S_n}{D_n} + b + \alpha) N_0 E_{AV} \alpha}{\omega D_n (\frac{1}{L_n^2} - \alpha^2 - \alpha b)} e^{t_1 (\frac{b}{2} + \sqrt{\left(\frac{b}{2}\right)^2 + \frac{1}{L_n^2}}} }{2 e^{\frac{bt_1}{2}} \left(\left(\frac{S_n}{D_n} + \frac{b}{2} \right) \sinh \sqrt{\left(\frac{b}{2}\right)^2 + \frac{1}{L_n^2}} t_1 + \sqrt{\left(\frac{b}{2}\right)^2 + \frac{1}{L_n^2}} \cosh \sqrt{\left(\frac{b}{2}\right)^2 + \frac{1}{L_n^2}} t_1 \right)}$$

This value of n_e can be substituted into Equation (46) to determine the electron current, however the general solution as a function of x is not of great interest. The total current for the cell will be the sum of the minority carrier currents at the junction, this assumes there is no generation and recombination within the junction region. The electron current density at the junction will be: (see next page for Equation 52)

The first term in Equation (52) represents the electron current due to normal junction action and the second term is the generated electron current caused by the beta particles.

The electric field intensity in the base region can be taken as zero, since the impurity density will be constant except very near the junction. The boundary conditions will be

$$p(t_1) = p_n (e^{av} - 1) \quad (53)$$

and

$$j_p(t_1 + t_2) = q S_p p_e(t_1 + t_2)$$

or

$$p'_e(t_1 + t_2) = - \frac{S_p}{D_p} p_e(t_1 + t_2), \quad (54)$$

where t_2 is the thickness of the base region. The differential equation describing the hole density in the base region will be

$$\frac{d^2 p_e}{dx^2} - \frac{p_e}{L_p^2} = - \frac{g}{D_p}, \quad (55)$$

which can be solved with the above boundary conditions to give Equation (56), see next page.

Hole current at the junction ($x=t_1$) will be

$$j_p = - q D_p \frac{dp_e}{dx}$$

or Equation (57), see next page.

$$j_n(t_1) = \frac{q L_n n_p}{\tau_n} \left\{ \frac{\left(\frac{1}{L_n} - \frac{S_n L_n b}{D_n z} \right) \tanh \sqrt{\left(\frac{b}{2} \right)^2 + \frac{1}{L_n^2}} t_1 + \frac{S_n L_n}{D_n} \sqrt{\left(\frac{b}{2} \right)^2 + \frac{1}{L_n^2}}}{\left(\frac{S_n}{D_n} + \frac{b}{2} \right) \tanh \sqrt{\left(\frac{b}{2} \right)^2 + \frac{1}{L_n^2}} t_1 + \sqrt{\frac{1}{L_n^2} + \left(\frac{b}{2} \right)^2}} \right\} (e^{aV} - 1)$$

$$- \frac{q L_n N_0 E_{av} \alpha e^{-\alpha t_1}}{\omega (1 - (\alpha L_n)^2 - \alpha b L_n^2)} \left\{ \frac{\left(\frac{1}{L_n} - \frac{S_n L_n b}{D_n z} \right) \tanh \sqrt{\left(\frac{b}{2} \right)^2 + \frac{1}{L_n^2}} t_1 + \frac{S_n L_n}{D_n} \sqrt{\left(\frac{b}{2} \right)^2 + \frac{1}{L_n^2}}}{\left(\frac{S_n}{D_n} + \frac{b}{2} \right) \tanh \sqrt{\left(\frac{b}{2} \right)^2 + \frac{1}{L_n^2}} t_1 + \sqrt{\frac{1}{L_n^2} + \left(\frac{b}{2} \right)^2}} \right. \\ \left. - \frac{\left(\frac{S_n L_n}{D_n} + b L_n + \alpha L_n \right) \sqrt{\left(\frac{b}{2} \right)^2 + \frac{1}{L_n^2}} e^{(\alpha + \frac{b}{2}) t_1} \operatorname{sech} \sqrt{\left(\frac{b}{2} \right)^2 + \frac{1}{L_n^2}} t_1}{\left(\frac{S_n}{D_n} + \frac{b}{2} \right) \tanh \sqrt{\left(\frac{b}{2} \right)^2 + \frac{1}{L_n^2}} t_1 + \sqrt{\left(\frac{b}{2} \right)^2 + \frac{1}{L_n^2}}} + (b + \alpha) L_n \right\} \quad (5.2)$$

$$P_e = P_n \left\{ \frac{\frac{S_p}{D_p} \sinh \frac{t_1 + t_2 - x}{L_p} + \frac{1}{L_p} \cosh \frac{t_1 + t_2 - x}{L_p}}{\frac{S_p}{D_p} \sinh \frac{t_2}{L_p} + \frac{1}{L_p} \cosh \frac{t_2}{L_p}} \right\} (e^{aV} - 1)$$

$$- \frac{N_0 E_{av} \alpha e^{-\alpha t_1}}{\omega D_p (\alpha^2 - \frac{1}{L_p^2})} \left\{ e^{-\alpha(x-t_1)} + \frac{-\frac{1}{L_p} \cosh \frac{t_1 + t_2 - x}{L_p} - \frac{S_p}{D_p} \sinh \frac{t_1 + t_2 - x}{L_p} + (\alpha - \frac{S_p}{D_p}) e^{-\alpha t_2} \sinh \frac{x-t_1}{L_p}}{\frac{S_p}{D_p} \sinh \frac{t_2}{L_p} + \frac{1}{L_p} \cosh \frac{t_2}{L_p}} \right\} \quad (56)$$

$$j_p(t_1) = \frac{q L_p P_n}{\tau_p} \left\{ \frac{\frac{S_p L_p}{D_p} + \tanh \frac{t_2}{L_p}}{\frac{S_p L_p}{D_p} \tanh \frac{t_2}{L_p} + 1} \right\} (e^{aV} - 1)$$

$$- \frac{q L_p N_0 E_{av} \alpha e^{-\alpha t_1}}{\omega (1 - \alpha^2 L_p^2)} \left\{ \frac{\frac{S_p L_p}{D_p} + \tanh \frac{t_2}{L_p} + (\alpha - \frac{S_p}{D_p}) L_p e^{-\alpha t_2} \operatorname{sech} \frac{t_2}{L_p}}{\frac{S_p L_p}{D_p} \tanh \frac{t_2}{L_p} + 1} - \alpha L_p \right\} \quad (57)$$

In Equation (57) let $t_2/L_p \gg 1$, then $\tanh t_2/L_p \approx 1$ and $\text{sech } t_2/L_p \ll 1$, also at the back junction $S_p \rightarrow \infty$ for an ohmic contact covering the entire back surface. With these approximations Equation (57) reduces to

$$j_p(t_1) \approx \frac{q L_p p_n}{\tau_p} (e^{aV} - 1) - \frac{q N_o E_{av} \alpha L_p e^{-\alpha t_1}}{\omega(1 + \alpha L_p)} \quad (58)$$

Approximations suitable for the simplification of Equation (52) are not available.

The total current density will be the sum of hole and electron current densities with the terms multiplying $(e^{aV} - 1)$ adding to give the reverse saturation current density and the other components add to give the total generated current density. Current density and voltage are related by the $e^{qV/kT}$ term, however experimental results yield a relationship of $e^{qV/nkT}$ with n equal to two or more. Assuming single-level recombination centers, a current arises from carriers which recombine or are generated in the depletion region. (62) This current will have a n of 2, however this assumes uniformly distributed recombination centers. If impurities causing recombination centers form as precipitates the values of n can be higher than 2. (63) Also, the current could be considered as due to both diffusion and recombination centers in the junction region resulting in a n between one and two.

The increase in the reverse saturation current with temperature is caused mainly by changes in minority carrier concentration. (64) Generated current will be relatively constant with temperature and the open circuit voltage will decrease with increasing temperature.

E. Experimental Results

The silicon cells studied were commercial units made by Hoffman Semiconductor Corporation. Three cells of each of the following types were obtained: N120CG-10, 120CG-10, 110C and 55C. The N120CG-10 is a gridded n/p cell with a rated room temperature efficiency of 10% and an active area of about 1.7 cm². The 120CG-10 is similar except that it is a p/n cell. The 110C is a 1x1 cm p/n cell with an efficiency of approximately 6%, while the 55C is a 1/2x1/2 cm p/n cell. Figures 19 through 22 are plots of the low light level characteristics of these cells. One hundred microamperes short circuit current was used as the reference level for the measurements.

Figure 19 compares the different sizes of cells for the same total short circuit current. The larger the cell area the greater the open circuit voltage and maximum power available. This was not expected, since the smaller cells should have lower reverse saturation currents because of the smaller area. A lower reverse saturation current for the same short circuit current should produce a larger open circuit voltage in the smaller cells. However, the larger open circuit voltage in larger cells is probably due to leakage current through surface channels at the edges of the smaller cells.

The p/n cells were not as uniform as the n/p cells, however they produced higher open circuit voltages and larger maximum powers. The typical p/n cell could be represented by a $n=2.08$ and $I_0=0.41 \mu\text{a}$ and produced $P_{mp}=17.05 \mu\text{ watts}$ for a $100 \mu\text{ amp}$. short circuit current. For a n/p cell, $n=1.77$, $I_0=0.39 \mu\text{a}$ and $P_{mp}=12.42 \mu\text{ watts}$. Also, a shunt resistance of about 20,000 ohms is needed to approximate the n/p cell. The principle difference between the p/n cells and the n/p cells seemed to be the shunt resistance present in the n/p cells. The variation of cell response with temperature is shown in Figures 21 and 22.

A gallium arsenide solar cell manufactured by the Radio Corporation of America was tested. The Type T-2428 is a gridded p/n cell with a rated efficiency of 7.5 to 8.4% and an active area of about 1.7 cm^2 . The volt-ampere characteristic of the cell for various temperatures is shown in Figure 23. The percentage change in open circuit voltage is less than for the silicon cells. Also, the maximum power decreases at a slower rate. Figure 24 is a plot of the current-voltage characteristics for a n/p silicon cell and the GaAs cell using direct sunlight as an energy source. The short circuit current for the silicon cell is twice that of the gallium-arsenide cell and its maximum power output would be greater. This is to be expected since the silicon cell has a higher rated efficiency.

Figure 25 is a plot of results obtained using a 15kv electron beam source to produce the electron-hole pairs in the semiconductor cell. The light from the filament produced a short circuit current of about $25 \mu\text{amps}$ for the silicon cells and $10 \mu\text{amps}$ for the GaAs cells. These values are small compared to the short circuit currents when the electron beam impinged on the sample, so practically all the electron-hole pairs are produced by the electron beam.

Because of the low energy of the electrons, the electron-hole pairs will be produced close to the surface and, therefore, close to the junction. Thus, the short circuit

currents should vary inversely with the energy required to create electron-hole pairs assuming a constant beam current. The ratio of the short circuit currents gives a value of about 6 ev to form electron-hole pairs in GaAs using a value of 4 ev for silicon. It was not possible to measure the beam current directly, therefore it undoubtedly varied slightly for the three sets of measurements.

F. Conclusions

A nuclear battery using GaAs or n/p silicon cells with Pm-147 as the source would be capable of operating for five to ten years with very little radiation damage. A $1 \times 2 \times 0.00071$ cm Pm-147 source (Pm_2O_3 form) containing about 8.4 curies should give a surface activity of 1 curie per square cm. Such a source should produce a short circuit current of about 150 μ amps in a silicon cell assuming 4 ev to produce electron-hole pairs. The above short circuit current was calculated using Equations (52) and (57) and typical solar cell parameters. The open circuit voltage at this level of activity would be about 300 millivolts. If Commercial solar cells are used in a nuclear battery, the antireflectivity coating on the surface of the cell should be removed.

A diffused base material can give a built-in field in the base region which will give more efficient collection and reduce the effect of radiation damage. (65,66)

At the present time, Gallium Arsenide solar cells are constructed in the laboratory rather than on a production line. As a result the GaAs cells are considerably more expensive than silicon cells. Also, the GaAs material itself is more expensive than silicon, so that GaAs cells will probably never be priced as low as silicon cells. However, GaAs cells have the advantage of a higher radiation damage threshold, higher open-circuit voltage and better temperature characteristics.

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ENERGY GAPS OF TETRAVALENT SEMICONDUCTORS
AS A FUNCTION OF $1/d^2$ (d =LATTICE CONSTANT)
(AFTER G. KOLM)

MELTING POINTS OF TETRAVALENT SEMICONDUCTORS
AS A FUNCTION $1/d^2$ (AFTER G. KOLM)

FIG. 3

RESISTIVITY VS CARRIER CONCENTRATION FOR
N-TYPE GALLIUM ARSENIDE (AFTER H. KRESSEL)

FIG. 4

FIG. 5

DIRECT RECOMBINATION LIFETIME
IN GALLIUM ARSENIDE

(AFTER J. HILIBRAND)

FIG. 6

FIG. 7

(AFTER A. B. PHILLIPS)

FIG. 8

RESISTANCE CHANGE WITH TIME OF P-TYPE SILICON.
CARRIERS GENERATED INITIALLY WITH STRONG LIGHT.

(AFTER J.R. HAYNES)

FIG. 9

TEMPERATURE DEPENDENCE OF
MOBILITY IN SILICON (AFTER W.W. GARTNER)

FIG. II

PLOT OF THE VALUES OF μ / μ_L VS μ_L / μ_i
(AFTER E.M. CONWELL)

VARIATION OF LIFETIME WITH IMPURITY CONTENT IN GERMANIUM
(AFTER R.N. HALL)

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FIG. 13

TEMPERATURE DEPENDENCE OF
MOBILITY IN GERMANIUM
(AFTER W.W. GARTNER)

FIGURE 14

DISPLACEMENT CROSS SECTION VS ENERGY

FIGURE 15

FIGURE 16 PLOT OF EQUATION (24)

FIGURE 17

FIGURE 18

TYPICAL DIFFUSION PROFILES
FOR ZINC IN GaAs

(L. H. GIBBONS JR.)

FIGURE 19

CURRENT-VOLTAGE CHARACTERISTICS VS SOLAR CELL SIZE

FIGURE 20

CURRENT-VOLTAGE CHARACTERISTIC OF SILICON SOLAR CELLS

P/N SILICON SOLAR CELL

FIGURE 21

CURRENT-VOLTAGE CHARACTERISTICS VS TEMPERATURE

N/P SILICON SOLAR CELL

FIGURE 22

CURRENT-VOLTAGE CHARACTERISTICS VS TEMPERATURE

FIGURE 23

CURRENT-VOLTAGE CHARACTERISTIC CURVES WITH TEMPERATURE AS A
PARAMETER FOR A GALLIUM ARSENIDE SOLAR CELL

FIGURE 24

CURRENT-VOLTAGE CHARACTERISTIC CURVES FOR SILICON AND GaAs SOLAR CELLS

FIGURE 25

CURRENT-VOLTAGE CHARACTERISTIC CURVES FOR ELECTRON BOMBARDED SOLAR CELLS