ON THE FEASIBILITY AND APPLICATION
OF OPTICAL P TO N INVERSION

by

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Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Electrical Engineering

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June 1985

Blacksburg, Virginia
ACKNOWLEDGEMENTS

The author wishes to sincerely thank Dr. L. C. Burton for serving as his graduate advisor and chairman of the graduate committee, without whose confident support and careful guidance this thesis would have remained a conjective.

Many thanks to Dr. R. H. Zallen and Dr. D. D. Chen for serving on the author's graduate committee.

The author would also like to thank and for their excellent work on the typing and figures in this thesis.

Finally, to , who gives her confidence and support to the author in all his endeavors.
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I. INTRODUCTION

Today's semiconductor devices are based on the thermal activation of shallow donors and acceptors placed in specific densities and geometries for the creation of active devices on a silicon or other suitable substrate. The donors and acceptors are diffused or ion implanted in the specific location desired using masks and various other required equipment. The ambient room temperature of the substrate provides sufficient energy to activate or ionize these defects providing n-type and p-type regions where desired. The combination of these n and p regions are then used to form active devices such as diodes, BJT's, FET's, and others. Overall, a given device may be viewed as a crystal which is heterogeneously doped and homogeneously heated or energized to create its active regions (refer to Fig. 1a).

Consider a reversal of this basic concept. Let the crystal be homogeneously doped and heterogeneously energized (Fig. 1b). The specific nature of the dopants and the energy source, however, may be considerably different from the thermal case. Active regions are created by selectively ionizing the dopants in the homogeneous substrate with energy which can be heterogeneously controlled (by means of intensity of geometry for example). It will be shown below that the active regions created will be electrically equivalent to the thermal situation normally used today.

The specific nature of the dopants and energy source has been left undefined. It is required that the effects of the dopants are negligible or inactive when no energy is being applied. This may be accomplished in a number of ways. One way is to lower the temperature of the
Fig. 1. a) Normal p-n junction (inhomogeneous doping, uniform T).
   b) Proposed case (homogeneous doping, inhomogeneous excitation).
substrate to a point in which the impurity effects have been essentially "frozen" out. Another method would be to make the impurities of a deep nature. This would have an effect similar to the temperature method, the deep impurity effects would be effectively eliminated even at room temperature. The energy source must be geometrically, intensity, and energy controllable, as well as being capable of operating on small scales (for integrated circuit applications). Thermal energy is not a sufficient source for these purposes. Electromagnetic energy, however, does fit all of these requirements. The result, then, is a substrate doped with deep defect levels at room or lower temperatures, and illuminated with light of a frequency necessary to activate the defect in a geometry necessary for active region creation.

Most photoconductive devices such as photo-detectors and photodiodes are used as bulk devices. These are uniformly illuminated in operation and are very different from the devices to be discussed in this thesis. In fact, the creation of active circuitry using the concept proposed here has not been found in the literature. Thus the analysis of the feasibility of this concept, and its applications, becomes increasingly important.

The objective of this thesis is to analyze the feasibility of this concept by examining the possibility of optically inverting a crystal from p-type to n-type and briefly illustrating some applications. The second chapter is dedicated to the feasibility study. This study analyzes a specific crystal and the conditions necessary to bring about inversion. The ensuing chapters briefly describe applications as applied to bipolar devices and eventually integrated circuits. The con-
cluding chapter illustrates some possible advantages of such a concept and the need for further study.
II. OPTICAL ACTIVATION

This chapter will be concerned with the analysis of a crystal doped with deep donors, at room temperature and uniformly illuminated to produce a possible p to n inversion.

2.1 Material Parameters and Assumptions

In order to achieve optical inversion a semiconductor crystal will be considered to have the following properties:

- \( E_g \) - energy band gap (eV)
- \( n_i \) - intrinsic carrier concentration (cm\(^{-3}\))
- \( d \) - thickness along irradiation axis (cm)
- \( u_n \) - electron mobility (cm\(^2\)/V•S)
- \( u_p \) - hole mobility (cm\(^2\)/V•S)
- \( V_n \) - electron thermal velocity (cm/sec)
- \( V_p \) - hole thermal velocity (cm/sec)

It is required here that the substrate be p-type in the dark and n-type in the light. This will be accomplished by doping the substrate with deep donors, which will provide an n-type source in the light, and shallow acceptors providing the p-type dark characteristic. More specifically, the deep donor will have the following characteristics:

- \( E_D \) - donor depth below the conduction band (eV)
- \( N_D \) - donor density (cm\(^{-3}\))
- \( N_D^+ \) - ionized donor density (cm\(^{-3}\))
- \( S_n \) - electron scattering cross-section (cm\(^2\))
$S_p$ - hole scattering cross-section (cm$^2$)

$S_L$ - photon scattering cross-section (cm$^2$)

The donor depth $E_D$ will be such that $E_D < E_g/2$. This is done to eliminate the donor level as an optical hole producer by the excitation of electrons from the valence band to the donor defect level.

The shallow acceptor parameters will be considered to be as follows:

$E_A$ - acceptor depth with respect to the valence band (eV)

$N_A$ - acceptor density (cm$^{-3}$)

$N_A^-$ - ionized acceptor density (cm$^{-3}$)

The acceptor depth is considered shallow enough to completely ionize the acceptors at the operating temperature which is room temperature ($T = 300^0K$) in this method. This means that $N_A^- = N_A$. This completes the material parameterization. The photon source is next considered.

The photon source to be used for the inversion process will have the following parameters:

$E_p$ - photon energy (eV)

$I$ - photon intensity (photons/cm$^2$•sec)

$\nu$ - photon frequency (Hz)

The photon energy will be considered such that $E_p = E_D$ so as to activate the donors. Restrictions on the intensity will effect the degree of inversion and will be considered later in the analysis.

In order to simplify the analysis, the following assumptions are made:
1) The active region thickness $d$ is made small enough that the light intensity $I$ causes uniform generation throughout the bulk of the exposed area. Therefore $n(x,y,t)$ will result in just $n(t)$ and all partial derivatives become total derivatives.

2) The crystal is absolutely pure and free from defects, including surface states, except for those purposely placed.

3) The substrate will be in steady state in both the dark and light cases. That is $\frac{dp}{dt} = \frac{dn}{dt} = 0$ for $t$ less than 0 (dark) and $t$ greater than some settling time for the process (light).

4) The reflection of the surface is constant and independent of wavelength.

A summation of the parameters and assumptions can be seen in Fig. 2.

2.2 Applicable Equations

In order to observe the inversion process, the electron and hole densities in both dark and light must be found. Comparison of these densities detail the degree of inversion. Determination of these densities must involve a solvable set of equations which describe the case being studied. The result involves three basic equations. The three equations are basic to semiconductor analysis and will be applied here as well.

The first equation is the rate equation, given as

$$\frac{dN}{dt} = G - R \quad 2.1$$
Fig. 2.  

a) Band diagram of purposed crystal

b) Physical picture of crystal, adhering to assumptions.
where \( N \) may be the density of electrons, holes, or filled defect levels, \( G \) is the generation rate (both thermal and optical) of carriers into the conduction band, valence band, or out of the donor level and \( R \) is the recombination rate of carriers from the levels. This equation may be used to find information about the occupation probability of the donor level. This probability is a very important function necessary for solution of the problem at hand. More about this function will be said during the actual analysis.

The second equation is the "Charge Neutrality Equation" (CNE). This equation will take the form

\[
n + N_A^- = p + N_D^+ \tag{2.2}
\]

where \( n \) and \( p \) are the electron and hole carrier concentrations respectively. Again the importance of the occupation probability can be seen here since the number of ionized donors will be given by

\[
N_D^+ = (1 - F_D)N_D \tag{2.3}
\]

where \( F_D \) is the probability of occupation of \( N_D \). Also, \( N_A^- = N_A^- \) from the assumption of 100% ionization. The result is the CNE with the form

\[
n + N_A^- = p + (1 - F_D)N_D \tag{2.4}
\]

More will be said about \( F_D \) later.

The third equation necessary for solution is

\[
pn = n_i^2 \tag{2.5}
\]

It will be used without proof. The intrinsic carrier concentration \( n_i \)
depends on the thermal state of the crystal. Thus the temperature and photon flux will directly effect \( n_t \). Since the crystal is considered to be at room temperature \( n_t \) will be its thermal equilibrium value in the dark case. The light, however, represents a form of excitation and thus pushes the substrate into a steady state non-thermal equilibrium situation. Therefore \( p n = c^2 \) where \( c^2 > n_t^2 \) in the light case in general. Thus Eqn. 2.5 will apply only in the dark case.

Armed with these three equations it now becomes possible to analyze the p to n inversion and show its feasibility. This will be considered in the following sections along with a numerical example for emphasis.

2.3 Analysis

This section will consider the analytical solution for the p and n carrier densities in the dark and light case. The process itself will be considered in its own section with the restrictions it imposes upon the inversion feasibility.

2.3.1 Dark Case

The densities sought here are p and n. The impurity densities are given as \( N_A \) and \( N_D \). Since the dark represents a thermal equilibrium situation the usual Fermi statistics apply. Therefore the rate equation need not be applied since the occupation probability is already defined from Fermi statistics. This probability is given by (2)

\[
F(E) = \left[ 1 + g \exp \left( \frac{E - E_F}{kT} \right) \right]^{-1}
\]

2.6
Assuming the Boltzmann approximation applies \((E - E_F >> kT)\) results in

\[
F(E) = \exp\left[\frac{-(E - E_F)}{kT}\right]
\]

where \(E_F\) is the Fermi level and the degeneracy \(g = 1\). This then leads to the following useful relations

\[
N^+ = N^g\left[1 - \exp\left[\frac{-(E_D - E_F)}{kT}\right]\right]
\]
\[
p = N_v\exp\left[\frac{-(E_F - E_v)}{kT}\right]
\]
\[
n = N_c\exp\left[\frac{-(E_c - E_F)}{kT}\right]
\]

As before the CNE and intrinsic carrier concentration take the forms

\[n + N_A = p + \left[1 - F(E_D)\right]N_D\]

and

\[pn = n_i^2\]

respectively.

The unknowns in this set of equations are \(p\), \(n\), and the location of \(E_F\). Since there are three unknowns and essentially five equations the set is completely solvable.

The solution can be obtained by first solving for the Fermi level and then substituting into Eqn. 2.9 and Eqn. 2.10 for \(p\) and \(n^{(1)}\). The Fermi level may be found as follows: Substituting Eqns. 2.8, 2.9, and 2.10 into the CNE yields

\[
N_c\exp\left[\frac{-(E_c - E_F)}{kT}\right] + N_A = N_v\exp\left[\frac{-(E_F - E_v)}{kT}\right]
\]

\[
+ N_D\left[1 - \exp\left[\frac{-(E_D - E_F)}{kT}\right]\right]
\]

All of the energies may be referenced to the valence band such that
\[ E_c - E_F = (E_c - E_v) - (E_F - E_v) = E_g - (E_F - E_v) \]

and

\[ E_D - E_F = (E_D - E_v) - (E_F - E_v) \]

where \( E_D - E_v \) is known. Substitution in Eqn. 2.11 gives

\[
N_c \exp\left[-E_g/kT\right] \exp\left[(E_F - E_v)/kT\right] + N_A = N_v \exp\left[-(E_F - E_v)/kT\right] + N_D \exp\left[-(E_D - E_v)/kT\right] \exp\left[(E_F - E_v)/kT\right]
\]

The only unknown here is \( E_F - E_v \). This value may be obtained numerically from the above equation. With the \( E_F - E_v \) value known \( p \) and \( n \) follow directly from Eqns. 2.9 and 2.10.

The next section details the analysis in the light.

2.3.2 Illuminated Case

In the light, Fermi statistics no longer apply because the light represents a form of excitation which pushes the crystal out of thermal equilibrium. Thus the Fermi level \( E_F \) is no longer appropriate. In nonthermal equilibrium, quasi-Fermi levels apply. These levels may be applied to all the carriers and defects involved. The occupation probability for the defect level may be found from the rate equation.

In the light, the rate equation as applied to the deep donors will take the form

\[
\frac{dN}{dt} = G_{Th} + G_{op} - R
\]

where \( N \) is the density of occupied donors, \( G_{Th} \) is the thermal generation rate, \( G_{op} \) is the optical generation rate and \( R \) is the recombination
rate. It will be assumed that $G_{Th}$ and $G_{op}$ are independent of each other. The generation and recombination processes are best seen with the aid of Fig. 3. In steady-state $\frac{dN}{dt} = 0$ and thus $G_{Th} + G_{op} - R = 0$.

The generation rates will be considered as the processes which excite electrons out of the donors. They may be considered as follows:

Step 1) The thermal release of electrons from the donor to the conduction band\(^{(2)}\),

$$G_1 = a_n N \quad 2.14$$

where $a_n$ is the thermal release rate given as\(^{(2)}\)

$$a_n = v_n s_n n e^{-\left(\frac{E_C - E_D}{kT}\right)} \quad 2.15$$

Also the occupied donor density $N$ may be given as

$$N = N_{DF} D \quad 2.16$$

Step 2) Scattering of an electron occupying a donor by a hole in the valence band\(^{(2)}\),

$$G_2 = V \left( s_p n_p F_p D \right) \quad 2.17$$

Step 3) Optical release of an electron from the donor by absorption of a photon to the conduction band,

$$G_3 = S_L n F_D \quad 2.18$$

(quantum efficiency $\eta = 1$ for simplicity).

This completes the generation rates.
The recombination rates will be those considered to scatter electrons into the donor level. With reference to Fig. 3b the recombination rates may be given as follows:

Step 1) Scattering of electrons in the conduction band by empty donor levels\(^{(2)}\),

\[ R_1 = \frac{V_S N_n N_D}{1 - F_D} \]  \hspace{1cm} 2.19

Step 2) Scattering of electrons in the valence band by empty donor levels, is equivalent to the thermal release of holes from the donor level, given as\(^{(2)}\)

\[ R_2 = a_p N_D (1 - F_D) \]  \hspace{1cm} 2.20

where \( a_p \) is the thermal release of holes given as\(^{(2)}\)

\[ a_p = V_S N_n \exp\left[-\frac{(E_D - E_V)}{kT}\right] \]  \hspace{1cm} 2.21

This completes the recombination rates since the photons have no direct recombinational effect on the donor level.

Combining the generation and recombination rates into the rate equation yields

\[
0 = a_n N_D F_D + v_{n} s_n p N_P F_D + s_L N_D F_D \\
- v_{n} s_n N_D (1 - F_D) - a_p N_D (1 - F_D)
\]

Solving this expression for \( F_D \) gives

\[
F_D = \frac{a_p + v_{n} s_n}{a_n + a_p + v_{n} s_n + v_{p} s_p + s_L} \]  \hspace{1cm} 2.22
Fig. 3. a) Generation as applied to the donor;
b) Recombination as applied to the donor.
(Various processes are described in the text)
This provides a promising form for the occupation probability of the donor level under illumination, since as \( I \) increases \( F_D \) decreases.

Now that the occupation probability has been deduced, the analysis may proceed by defining the remaining equations necessary for solution.

The rate equation may be applied to the conduction and valence bands to yield further relations. The application, however, will involve an additional term since band to band phenomena come into play. If the band gap thermal generation rate of electron-hole pairs is neglected and the recombination rate has the form

\[
R = Bpn
\]  

then the rate equations for conduction electrons and valence holes take the form

\[
\frac{dn}{dt} = 0 = \alpha n N_D F_D + s_L N_L F_L - v_s n n_D (1 - F_D) - Bpn
\]  

\[
\frac{dp}{dt} = 0 = \alpha p N_D (1 - F_D) - v_s p n_D F_D - Bpn
\]

respectively.

The next equation that may be considered is the CNE given as

\[
n + N_A = P + N_D (1 - F_D)
\]

These four relationships define a solvable set for \( p \) and \( n \) in steady state. In fact only three of the four equations are necessary for solution. Choosing Eqn. 2.22, Eqn. 2.25, and Eqn. 2.4 results in the following algebraic progression. Substitute Eqn. 2.22 into Eqn. 2.25 to give
\[ a_p - \frac{(a_p + V S n)(a_p + V S p)}{a_p + a_p + V S n + V S p + S L} \cdot B_p n = 0 \quad 2.26 \]

Eqn. 2.4 (with the substitution of Eqn. 2.22) gives the relation

\[ n - p + N_A - N_D - \frac{N_D(a_p + V S n)}{a_p + a_p + V S n + V S p + S L} = 0 \quad 2.27 \]

Equations 2.26 and 2.27 may now be solved simultaneously for \( p \) and \( n \). This will not be done here since it adds nothing to the present discussion. In fact it is obvious that the result would be a rather cumbersome relationship as well as difficult to obtain.

The solutions obtained for the dark and light cases say nothing of the inversion process itself. The inspection of this process is done in the next section. This inspection will yield restrictions on the parameters of the donors, crystal, and light intensity. These restrictions are necessary for the process to be feasible, and will in fact, represent a demonstration of feasibility.

### 2.4 Feasibility of Proposed Technique

It is projected that the carrier inversion process will proceed along the following lines. In the dark the acceptors are completely ionized and the donors are partially ionized. The densities of the dopants are such that \( p > n \) making the crystal \( p \) type. With incident photons there will be an initial glitch in the conduction electron population. These conduction electrons begin to recombine with the holes either directly or through recombination centers. The electron and hole populations decrease in parallel, and since \( n_o > p_o \) in the light, the
resulting steady state will be an n-type crystal. This is the desired inversion. The magnitude of this inversion will depend on the donor density and light intensity. From this process, then, the restrictions become evident.

The first restriction is that \( n > p \) at \( t = 0 \). This will guarantee that as the process proceeds the resulting equilibrium will be n-type. The second restriction is that \( \frac{dp}{dt} < 0 \) for \( t > 0 \). This will guarantee that the required decrease will occur as prescribed. Thus if these restrictions are satisfied the inversion process will have a high probability of occurring as described.

For the analysis, the following conditions will be assumed:

1) \( p_0 = p_- \) at \( t = 0 \). This says that the population of holes does not change when the light initiated. Thus the initial value is the same as the dark steady state value.

2) \( F_{D0} < F_{D-} \). The initial occupation is less than the dark steady state value. \( F_D \) will also be less than \( F_{D-} \) in the light at steady state.

3) \( n_0 = N_D(F_{D-} - F_{D0}) \) at \( t = 0 \). The initial value of \( n \) will be the difference between the occupations at \( t = 0 \). The equilibrium value of \( n \) in the light will be the difference in the equilibrium occupation in the dark and light also.

With these definitions, the restrictions may be analytically evaluated.

The first restriction \((n_0 > p_0)\) will have the form

\[
N_D(F_{D-} - F_{D0}) > p_0
\]

2.28a
which simplifies to

\[ F_{DO} < F_D - \frac{p_o}{N_D} \quad \text{2.28b} \]

Substituting for \( F_{DO} \) from Eqn. 2.21 gives

\[ I_o > \frac{1}{L} \left[ \frac{a + V_S n_o}{p_D - \frac{p_o}{N_D}} - a - a_p - V_S n_o - V_S p_o \right] \quad \text{2.29} \]

This inequality places a lower limit on the light intensity. If \( I_o \) does satisfy this relation, \( n_o \) will be greater than \( p_o \). The next restriction places an upper limit on \( I_o \) for inversion.

The second restriction requires a bit more analysis. In other words the recombination process must be identified. In this analysis two processes will be considered. The first is simple band to band recombination and the second is recombination via a recombination center.

The band to band recombination rate has the form, as before, \( R = B p_n \), where \( B \) is the probability of electron-hole recombination. The band gap of the semi-conductor will be considered wide enough to neglect the thermal electron-hole pair generation rate. Thus the rate equation for holes may be written as

\[ \frac{dp}{dt} = a_p N_D (1 - F_p) - V_S p_o N_D F_D - B p_n \quad \text{2.30} \]

substituting the assumptions for \( t = 0 \) into this equation gives

\[ \frac{dp}{dt} = a_p \left( 1 - F_{DO} \right) - V_S p_o F_{DO} - B p_o \left( F_D - F_{DO} \right) \quad \text{2.31} \]

resulting in
\[ a_p F DO + V_p S p_o F DO + B_p o F D_ - > a_p + B_p o F DO \] 2.32

It will aid the restriction formulation to reduce this inequality. It can be seen that \( B_p o F D_ - > B_p o F DO \), by assumption 2. Also \( a_p F DO < a_p \) since \( F DO < 1 \). Therefore consider

\[ V_p S p_o F DO + B_p o F DO > a_p \]

From this inequality consider \( V_p S p_o F DO > a_p \). This results in \( F DO > F D_ - \) which is untrue by assumption 2. Therefore consider lastly

\[ B_p o F DO > a_p \] 2.33

Rearrangement gives \( F DO > \frac{a_p}{B_p o} \). Substituting for \( F DO \) using Eqn. 2.22 gives

\[ I_o < \frac{1}{S_L} \left( \frac{B_p o (a_n + V_p S n_o)}{a_p} - a_n - a_p - V_p S n_o - V_p S p_o \right) \] 2.34

This upper bound reflects the limitation imposed by the thermal release of holes from the donor level. If the donor becomes too empty, the hole release rate will begin to exceed the recombination rate, thereby blocking inversion. This upper limit in practice, however, may be several orders of magnitude higher than the lower limit. Since the lower limit will usually determine the operation point, the upper limit will be considered a theoretical rather than practical limitation.

If the two inequalities are satisfied then \( n_o > p_o \) and \( \frac{dp}{dt} < 0 \) will be true, resulting in inversion as described. These inequalities, however, must themselves obey some restrictions to be reasonable. These restrictions stem from the fact that if \( a < b < c \), where \( b \) is a positive
real number, then $a < c$ and $a > 0$ and $c > 0$ (since $I_o > 0$). This results (after substitution and simplification of the inequalities) in the following relations:

\[ \frac{1}{F_D - \frac{p_o}{N_D}} < \frac{Bp_o}{a_p} \quad 2.35 \]

and

\[ \frac{Bp_o}{S_L a_p} > D \quad 2.36 \]

and

\[ \frac{1}{S_L \left(F_D - \frac{p_o}{N_D}\right)} > D \quad 2.37 \]

where

\[ D = \frac{a_n + a_p + V_S n_o + V_S p_o}{a_n + V_S n_o} \]

There exists some redundancy here. It will be sufficient that Eqn. 2.35 and Eqn. 2.37 are true, which will imply Eqn. 2.36. These are material conditions that must be satisfied by the substrate and the dopants. Their fulfillment causes the intensity inequalities to be reasonable. The recombination probability $B$, however, may be a bigger problem for indirect gap materials than for direct gap materials\(^{(13)}\). In order to help guarantee a feasible process a recombination center will be considered\(^{(13)}\).

A recombination center is assumed added to improve upon the indirect gap material. This center will be located in the band shown in Fig. 4 so that it is not an optical electron or hole producer. The rate equation for holes may then be expressed as
Fig. 4. Recombination center band limitation to prevent optical interference.
\[
\frac{dp}{dt} = a_p N_D (1 - F_D) + a_{PR} N_R (1 - F_R) - V S_p P_D N_D - V S_{PR} p F_N N_R
\]

where \( N_R \) is the center density, \( S_{PR} \) is the hole scattering cross-section and \( F_R \) is the occupation probability given by (2)

\[
F_R = \frac{a_{nR} + V S_{nR} n}{a_{PR} + a_{nR} + V S_{nR} n + V S_{PR} p}
\]

The rate equation may be written as

\[
a_p N_D (1 - F_D) + a_{PR} N_R (1 - F_R) - V S_p P_D N_D - V S_{PR} p F_N N_R < 0
\]

Which may be rearranged to give

\[
F_{DO} > \frac{a_p N_D (1 - F_D) + a_{PR} N_R (1 - F_R) - V S_{PR} p F_N N_R}{N_D (a_p + V S_{PR} p)}
\]

Substituting for \( F_{DO} \) from Eqn. 2.22 will yield an upper limit for \( I_o \) as before. The lower limit (Eqn. 2.29) also still applies. These then form the intensity restrictions and may also be manipulated to yield the material parameters as before. The actual substitutions and simplifications have not been done here to avoid needless complexity since they are rather cumbersome already. The principles for inversion are the same regardless. The recombination center has the advantage of being designable. This means that centers may be chosen from a wider variety of sources than substrates so as to fit specific needs (4). Either, however, is achievable and realizable with presently known or new materials.
The dependence of the p to n inversion on time can be found by inspecting $\frac{dp}{dt}$. If the recombination rate is governed by band to band action then

$$\frac{dp}{dt} = a_p N_D (1 - F_D) - V_S p N_D F_D + B_{pn}$$

If it is assumed that $n$ and $F_D$ remain relatively constant with the time with respect to $p$ then the differential rate equation takes the form

$$\frac{dp}{dt} + (V_S N_F + B_{n_0}) p = a_p N_D (1 - F_D)$$  \hspace{1cm} \text{2.40}$$

This equation has the solution

$$p(t) = Ae^{-ct} + pf$$  \hspace{1cm} \text{2.41a}$$

where

$$A = P_0 - \frac{a_p N_D (1 - F_D)}{(V_S N_F + B_{n_0})}$$

and

$$p_f = \frac{a_p N_D (1 - F_D)}{(V_S N_F + B_{n_0})}$$  \hspace{1cm} \text{2.41b}$$

and

$$C = \frac{V_S N_F}{p_p d'} + B_{n_0}$$  \hspace{1cm} \text{2.41c}$$

The constant $p_f$ represents the steady-state $p$ concentration. Since the recombination depends on the mutual interaction of electrons and holes, the $n(t)$ concentration will parallel $p(t)$. The final $n$ concentration, $n_f$, may be solved for using the CNE and occupation $F_D$ with $p_f$ substituted. This gives (after some simplification)
This is an approximation but does imply if $n_f > p_f$ since $N_D > N_A$. This is the inversion desired.

The time required for the inversion process, initialization to steady state, may be estimated from Eqn. 2.4.1c. If the parameters from section 2.5 are considered a time on the order of a couple of milliseconds is obtained. For a direct gap material this time may drop to a nanosecond or less. Thus the time range for varying densities, carriers, and crystals varies over a very wide range. This could be important in switching device applications.

The results of the restrictions and the carrier densities as a function of time as shown in Fig. 5, are an illustration of the carrier inversion process as treated in this thesis.

This analysis has been very ideal and many assumptions have been made. A more thorough treatment is beyond the scope and indeed purpose of this thesis. The results presented here are thus approximations but do not confirm the feasibility of $p$ to $n$ carrier inversion provided the restrictions are satisfied by the proper substrate, donors, and light intensities. An illustrative numerical example using existing materials is done in the next section.

2.5 Numerical Example

A brief numerical example will help illustrate the feasibility of this concept. In this example it will be assumed that the substrate is
Fig. 5. Expected inversion process vs. time (carrier densities).
crystalline silicon, Si, doped with deep donor sulfur, S, and compensated by boron, B. It will be assumed that all other material specifications and assumptions are met as described in Section 2.1. The parameters are summarized in Table 1(1,4). Figure 6 gives the band diagram for the example.

This example will be considered as a design problem in that \( n \) and \( p \) will be given values in both dark and light. The quantities \( N_D, N_A, \) and \( I \) are sought as design parameters. This process is simpler and more illustrative.

Let \( p = 10^{12} \) which results in \( n = 2.1 \times 10^8 \) from Eqn. 2.5 in the dark. This specifies the Fermi level, \( E_F \), from either Eqn. 2.9 for Eqn. 2.10 as \( E_F - E_V = .403 \text{eV} \). This gives \( E_{D1} - E_F = .197 \text{eV} \), \( E_{D2} - E_F = .347 \text{eV} \), and \( E_{D3} - E_F = .537 \text{eV} \) for use in the occupation probability, (Eqn. 2.7). The occupation for each level is thus \( F_{D1} = 3.78 \times 10^{-4} \), \( F_{D2} = 9.37 \times 10^{-7} \), and \( F_{D3} = 4.69 \times 10^{-1} \). The CNE will have the form

\[
n + N_A = p + N_D[(1 - F_{D1}) + (1 - F_{D2}) + 1 - F_{D3})]
\]

for this triple level donor. Since \( F_{D1} \gg F_{D2} \gg F_{D3} \) results in

\[
N_A = 10^{12} + N_D(3 - 3.78 \times 10^{-4}) \sim 2.43
\]

This expression for \( N_A \) is now carried into the light case to yield \( N_A \) from \( N_D \).

In the light it is already known that

\[
N_D(F_{D1} - F_{D10}) = n_0 \sim 2.44
\]
Fig. 6. Band diagram of numerical example.
Table 1  a) Si parameters;  b) S parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n_i)</td>
<td>(1.45 \times 10^{10}\text{cm}^{-3})</td>
</tr>
<tr>
<td>(N_v)</td>
<td>(1.04 \times 10^{19}\text{cm}^{-3})</td>
</tr>
<tr>
<td>(N_C)</td>
<td>(2.8 \times 10^{19}\text{cm}^{-3})</td>
</tr>
<tr>
<td>(E_g)</td>
<td>1.12eV</td>
</tr>
<tr>
<td>(kT (T = 300^\circ\text{K}))</td>
<td>0.026eV</td>
</tr>
<tr>
<td>(V_n)</td>
<td>(5 \times 10^6\text{cm}\cdot\text{sec}^{-1})</td>
</tr>
<tr>
<td>(V_P)</td>
<td>(5 \times 10^6\text{cm}\cdot\text{sec}^{-1})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S_n)</td>
<td>(10^{-17}\text{cm}^2\text{(typ)})</td>
</tr>
<tr>
<td>(S_P^*)</td>
<td>(10^{-21}\text{cm}^2\text{(typ)})</td>
</tr>
<tr>
<td>(S_L)</td>
<td>(10^{-14}\text{cm}^2\text{(typ)})</td>
</tr>
</tbody>
</table>

\(\text{$S_P^*$ small due to double ionization($S^{++}$).}\)
where \( F_{D10} \) is the initial occupation. The occupation \( F_{D10} \) is specified by Eqn. 2.22 except that \( I_o \) is not given.

\( I_o \) may be specified by the restrictions Eqn. 2.29 and Eqn. 2.34. Even though this is SI with a low \( B \) it will be assumed since \( S_p \) is so small that the material parameter Eqn. 2.36 is satisfied. Also \( I_o \) will be chosen to be slightly greater than the lower limit. This will automatically satisfy Eqns. 2.35 and 2.37. \( I_o \) is

\[ I_o = (x)(\text{lower limit}) \]

where \( x > 1 \). If this is substituted into Eqn. 2.22 where all terms except \( \frac{a_n + V_S}{n_o n_n} \) are neglected results in

\[ F_{D} = \frac{F_{D10}}{x} - \frac{p_o}{xN_D} \]

Substituting this into Eqn. 2.44 yields

\[ N_D = \frac{n_o - \frac{p_o}{x}}{(1 - \frac{1}{x})F_{D10}} \]

If \( n_o = 2 \times 10^{12} \) when the light is initiated, \( x = 1.1 \), and \( p_o = 10^{12} \) from the dark gives \( N_D = 3.2011 \times 10^{16} \) and \( N_A = 9.6021 \times 10^{16} \) from Eqn. 2.43. The final values, \( n_f \) and \( p_f \) can be taken from Eqn. 2.41b and Eqn. 2.42 respectively(13). The results are tabulated in Table 2.
Table 2. Numerical results from example.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_A$</td>
<td>$9.6021 \times 10^{16}\text{cm}^{-3}$</td>
</tr>
<tr>
<td>$N_D$</td>
<td>$3.2011 \times 10^{16}\text{cm}^{-3}$</td>
</tr>
<tr>
<td>$I_0$</td>
<td>$\sim 2.7 \times 10^{19}\text{photons/cm}^2$</td>
</tr>
<tr>
<td>$p$ (dark)</td>
<td>$1 \times 10^{12}\text{cm}^{-3}$</td>
</tr>
<tr>
<td>$n$ (dark)</td>
<td>$2.1 \times 10^8\text{cm}^{-3}$</td>
</tr>
<tr>
<td>$p_0$</td>
<td>$1 \times 10^{12}\text{cm}^{-3}$</td>
</tr>
<tr>
<td>$n_0$</td>
<td>$2 \times 10^{12}\text{cm}^{-3}$</td>
</tr>
<tr>
<td>$p_f$ (final)</td>
<td>$\sim 4.5 \times 10^9\text{cm}^{-3}$</td>
</tr>
<tr>
<td>$n_f$ (final)</td>
<td>$\sim 6.4 \times 10^{11}\text{cm}^{-3}$</td>
</tr>
<tr>
<td>$F_{Dl-}$</td>
<td>$3.78 \times 10^{-4}$</td>
</tr>
<tr>
<td>$P$</td>
<td>$\sim\text{2W/cm}^2$</td>
</tr>
<tr>
<td>$x$</td>
<td>1.1</td>
</tr>
</tbody>
</table>
The light intensity $I_o$ implies that the incident power should be approximately $P = 2.16$ W/cm$^2$. This is a somewhat large number but it is rare that an entire square centimeter would need inversion in any application. Indeed micro-circuits would probably require less than 10% of this power (~200 mW/cm$^2$). Even though this is a rather high intensity, it is not unobtainable\(^{(11)}\).

This numerical example poses the question, "For what range of parameters is the inversion process feasible?" The answer to this question is examined in the following section.

2.6 Range of Feasibility

The previous section illustrated an example which resulted in a rather low carrier concentration ($p_o = 10^{12}$, $n_f = 10^{12}$), moderate dopant density ($N_A = 9 \times 10^{16}$), and rather high light intensity ($2W/cm^2$). This implies that the inversion process may be limited. In other words, if a desired carrier concentration results in an unreasonably high (or low) dopant density and/or light intensity then the inversion may be unfeasible. It will be considered here that $N_{D,A} < 10^{20} cm^{-3}$ and $P < 2W/cm^2$ will be upper limits for feasibility\(^{(1,11)}\). These are extreme values, but they are achievable. The range of the carrier concentrations remain as a last characterization of feasibility and indeed usefulness.

For the analysis, a silicon crystal will be considered doped with a double donor (one deep = .55eV and one shallow) and a shallow acceptor.

The dopants will not be identified, instead, the scattering cross-sections will be allowed to vary. In this way the nature of an optimum deep donor may be specified which will produce the most feasible and most
useful inversion. The resultant optimum donor may or may not exist and would be a subject for future study.

The scattering cross-sections will be allowed to vary as follows:\(^{(4)}\):

\[
10^{-12} < S_L < 10^{-13}
\]

\[
10^{-12} < S_n < 10^{-19}
\]

and

\[
10^{-14} < S_p < 10^{-22}
\]

Also, \(x = 2\) will be used. Using these values, as in Section 2.5, and a simple BASIC program the values shown in Table 3 were obtained. (The program is shown in Appendix A.) A definite trend exists which imposes some rules for feasibility. First of all, a large light scattering cross-section, \(S_L\), is very desirable since it will allow for a reasonable light power. Toward this end, a small electron scattering cross-section would also aid in reducing the optical power necessary\(^{(19)}\). The hole scattering cross-section should be small also to reduce \(p_f\) to an inverted condition\(^{(19)}\). This restriction, however, may be traded off with the use of a direct bandgap crystal to increase \(B\) as in Eqn. 2.41b. The carrier concentrations tend to be on the small side, however, a rectifying junction can still theoretically be made. Apparently the light intensity poses the biggest problem while the impurity density becomes a limiting factor, when larger carrier concentrations are desired. In this case, however, \(x = 2\) was chosen. If \(x\) is allowed to approach its lowest value, \(x = 1\), the light intensity may be a little less than halved. This would, however, push up the impurity concentrations, which is a trade-off. Thus it can be seen that the range of feasibility and usefulness is dependent
Table 3. Range of parameters for feasibility.
(Each row represents the requirements for an invertable crystal with the light power indicated for inversion.)

<table>
<thead>
<tr>
<th>SN</th>
<th>cm²</th>
<th>SP</th>
<th>SL</th>
<th>NO</th>
<th>PO</th>
<th>(cm⁻³) ND</th>
<th>NA</th>
<th>NF</th>
<th>PF</th>
<th>W/cm² P</th>
</tr>
</thead>
<tbody>
<tr>
<td>10⁻¹²</td>
<td>10⁻¹⁴</td>
<td>10⁻¹²</td>
<td>10¹¹</td>
<td>10¹⁰</td>
<td>9.16x10¹⁰</td>
<td>14.7x10¹⁰</td>
<td>2.8x10¹⁰</td>
<td>0.4x10¹⁰</td>
<td>.098</td>
<td></td>
</tr>
<tr>
<td>10⁻¹⁵</td>
<td>10⁻¹⁴</td>
<td>10⁻¹²</td>
<td>2x10¹²</td>
<td>1x10¹²</td>
<td>1.1x10¹⁵</td>
<td>2.2x10¹⁵</td>
<td>3.74x10¹²</td>
<td>1.6x10¹²</td>
<td>1.19</td>
<td></td>
</tr>
<tr>
<td>10⁻¹⁵</td>
<td>10⁻¹⁸</td>
<td>10⁻¹²</td>
<td>2x10¹²</td>
<td>1x10¹²</td>
<td>1.1x10¹⁵</td>
<td>2.2x10¹⁵</td>
<td>2.5x10¹²</td>
<td>6.8x10⁹</td>
<td>1.19</td>
<td></td>
</tr>
<tr>
<td>10⁻¹⁷</td>
<td>10⁻²⁰</td>
<td>10⁻¹²</td>
<td>2x10¹³</td>
<td>1x10¹⁷</td>
<td>1.2x10¹⁷</td>
<td>2.42x10¹⁷</td>
<td>2.6x10¹³</td>
<td>7.4x10⁹</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>10⁻¹⁷</td>
<td>10⁻²⁰</td>
<td>10⁻¹⁴</td>
<td>2x10¹²</td>
<td>10¹²</td>
<td>1.1x10¹⁵</td>
<td>2.2x10¹⁵</td>
<td>2.6x10¹²</td>
<td>7.4x10⁹</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td>10⁻²⁰</td>
<td>10⁻²¹</td>
<td>10⁻¹³</td>
<td>2x10¹³</td>
<td>10¹³</td>
<td>1.2x10¹⁷</td>
<td>2.4x10⁷</td>
<td>2.5x10¹³</td>
<td>7.4x10⁸</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>10⁻²⁰</td>
<td>10⁻²¹</td>
<td>10⁻¹³</td>
<td>2x10¹⁴</td>
<td>10¹³</td>
<td>1.3x10¹⁹</td>
<td>2.64x10¹⁹</td>
<td>2.5x10¹⁴</td>
<td>8.21x10¹⁰</td>
<td>1.43</td>
<td></td>
</tr>
<tr>
<td>10⁻²⁰</td>
<td>10⁻²²</td>
<td>10⁻¹²</td>
<td>2x10¹⁴</td>
<td>10¹⁴</td>
<td>1.32x10¹⁹</td>
<td>2.64x10¹⁹</td>
<td>2.5x10¹⁴</td>
<td>8.2x10⁹</td>
<td>.143</td>
<td></td>
</tr>
</tbody>
</table>
upon several factors all of which are more or less controllable by specific impurity choices.

It is obvious from this section that the feasibility exists in a small range. This range, although narrow, still offers some real possibilities. It is also obvious that much study of varying crystal substrates, deep donors, and impurity combinations is necessary. This is not the purpose of this paper. The purpose is to show feasibility, which has been done, and display that it may be realizable (shown in this section).

The next section explores the creation of a p-n junction using this technique. Also some possible applications are discussed.

2.7 P-N Junctions and Applications

Since the 1950's, the bipolar p-n junction transistor has been the most important single element in electronics. These junctions are normally produced by diffusion techniques\(^5\). With the optical inversion process feasible a different technique can potentially be used to create a similar p-n junction. The junction can be made by homogeneously doping a substrate with the defect levels as specified in the previous sections. Next, a mask or block may be placed over half of the material. Following this the substrate is exposed to the proper illumination. The exposed portion is inverted to n-type while the shaded region remains p-type, forming the desired p-n junction (refer to Fig. 7a).

This junction may be modeled as abrupt since the nature of production is optical which can be made nearly abrupt\(^6\). This abrupt junction
Fig. 7.  

a) Optical P-N junction creation;  
b) View of junction and carrier concentrations.
may be treated in the usual manner of a typical diffused diode except
that \( pn = n_i^2 \) does not apply in the lighted side. Thus the current
density equations must be applied with care. It is still true that \(^{(1)}\)

\[
\begin{align*}
J_p &= 0 = qu_n (pE - \frac{kT \, dp}{q \, dx}) \quad 2.47 \\
J_n &= 0 = qu_n (nE + \frac{kT \, dn}{q \, dx}) \quad 2.48
\end{align*}
\]

in the depletion region. A problem arises during the integration of this
equation for the built in voltage, \( V_{bi} \), since the carrier densities
extend different lengths into the bulk. This means \( x_n \) and \( x_p \), light
side, are at different locations. If this is taken as a fringing effect
and neglected as a small difference then it may be seen from Eqn. 2.47
that

\[
V_{bi} = \frac{kT}{q} \ln\left(\frac{p_p}{p_f}\right) \quad 2.49
\]

where \( p_p \) is the \( p \) density in the dark side. The hole current equation
was chosen because it is expected that \( x_p < x_n \) since the hole population
difference is less than the electron population difference and the hole
mobility is less than the electron mobility in general. With \( V_{bi} \) defined
the diode current takes the usual form \(^{(1)}\)

\[
J = J_s \left( e^{qV/kT} - 1 \right) \quad 2.50
\]

where \( J_s \) is the reverse saturation current given as \(^{(1)}\)

\[
J_s = \frac{qD_p p_n}{L_p} + \frac{qD_n n_n}{L_n}
\]
These equations may be evaluated for the example of Section 2.5 with 
$q = 1.6 \times 10^{-19}$, $D_p = 12.4 \text{cm}^2/\text{s}$, $D_n = 34.9 \text{cm}^2/\text{s}$, $L_p = L_n \approx 1 \text{cm (max)}$, $p_{no}$ 
$= p_f = 4.5 \times 10^9 \text{cm}^{-3}$, $n_{po} = n = 1.1 \times 10^8 \text{cm}^{-3}$. The result is 

$$J = 9.54 \times 10^{-9} (e^{40V} - 1) \text{A}$$

and $V_{bi} = .135 \text{V}$. This gives an I-V characteristic as shown in Fig. 8.

The result is that the optical inversion process can provide a different and potentially useful technique for producing p-n junctions. The geometry of this junction is controlled by the blocking mask. Changes in the junction are accomplished by merely controlling the mask pattern and light intensity blocking power. This is a potentially useful advantage.

Now that the p-n junction has been redefined, the natural progression is to the BJT. This device may take the form of a pnp or npn type structure. Again, the devices may be produced using the correct blocking masks as shown in Fig. 9. The base width is limited by the light diffraction as shown in Fig. 10. This limitation is minor in the applications considered.

It is obvious at this point that a variety of p-n structures becomes possible. Thus the usual devices produced today by diffusion may be made optically, not only active structures, but passive as well. Some of these structure are shown in Fig. 11.

All of the components thus far extend completely through the host substrate. The attenuation of the light is thus not a factor. If the substrate thickness $d$ increases, the attenuation does become a factor. If the attenuation is $\alpha$, the intensity will drop off as
Fig. 8. I-V characteristic of diode from Section 2.5 example.
Fig. 9  NPN and PNP junction transistor structures.
Fig. 10 Diffraction of light through mask causing base width limitation.
Fig. 11 Passive components (conductor, resistor).
I(x) = I_o e^{-\alpha x}

where I_o is the intensity at the surface (x = 0) and x is the depth into the crystal. Thus as the light intensity decreases the area will be smaller along x until the intensity no longer satisfies the conditions for inversion and the crystal again becomes p-type. This process is illustrated in Fig. 12. This again opens the possibility for several structures for active and passive elements. If illumination is allowed from both sides, some possible structures may be as shown in Fig. 13.

The ability to create p-n junctions using this p to n inversion provides some rather interesting results. The next section will deal with other forms of photoconductivity (intrinsic, extrinsic) and some potential applications. The sections following this will combine some of these techniques and applications to culminate into a proposal of integrated circuit fabrication. A few other interesting possibilities are also explored.
Fig. 12 Attenuation of light and carrier profiles versus distance into the crystal.
Fig. 13  Attenuation structures.

a)  Illumination from the top to form p-n junction diode.

b)  Illumination from both sides to produce BJT.
III. QUALITATIVE REVIEW OF OTHER PHOTOCONDUCTIVITY AND APPLICATIONS

The previous section dealt with a form of extrinsic photoconductivity in a specific case. The more common phenomena of intrinsic photoconductivity as well as extrinsic will be considered in this chapter. These two types will be treated in a qualitative manner. They will also be applied to show some useful architectures.

This section has been included as a supplement to the p-n inversion case and to extend the range of applications of both the p-n inversion and normal photoconductive cases. This will become apparent toward the end of this section and the beginning of the next.

3.1 Intrinsic and Extrinsic

Intrinsic photoconductivity is the most common photoconductive phenomena and is by far the most used\(^{(3)}\). It involves the creation of an electron-hole pair by the absorption of an incoming photon with energy \(E_p = E_g\) (Fig. 14a). The attenuation of light is usually very strong, depending on the semiconductor. GaAs, for instance, attenuates most of the light within \(0.1-1\,\mu m\) from the surface\(^{(11)}\). Such strong absorption produces a sheet of electron-hole pairs which proceed to diffuse into the crystal (Fig. 14b).

This diffusion is governed by several determining factors. These factors are the diffusion constant \(D\) and the carrier lifetime \(\tau\), which are related by

\[
L = (D\tau)^{1/2}
\]
where $L$ is the diffusion length. This length gives information about the distance the carriers diffuse before recombining. Since the application here is directed toward microcircuitry, $L$ places a restriction on line widths possible. This restriction can best be illustrated by a brief example.

For this example the diffusion length equation and

$$\Delta n = G_{op} \tau_n$$

will be used, where $G_{op}$ is the optical generation rate and $\Delta n$ are the excess electrons generated. It will be assumed here that $G_{op} = \eta J_0$ where $J_0$ is the photon density. Also $\eta$ will be considered to be 1.

Assume that the crystal is a sample of GaAs doped with enough recombination centers to make $\tau_n = 10^{-10}$ sec. Only the electrons will be considered here since their mobilities are larger than those for holes. Thus $D = D_n$ where $D_n = 221 \text{ cm}^2/\text{sec}$ for GaAs$^{(1)}$. This yields a diffusion length of $L = 1.5 \mu\text{m}$. This will allow a line of approximately $5 \mu\text{m}$ in width.

The power required to create this line will depend on the carrier density desired. If it is desired that $\Delta n = 10^{12} \text{ cm}^{-3}$, then $J_0 = 10^{22}$ photons·sec$^{-1}$·cm$^{-3}$. Since absorption may be considered to occur in $\sim 1 \mu\text{m}$ from the surface, a rough approximation for these carriers would require a power of $23.2\text{mW}$ for a surface area of $1 \text{cm}^2$. The light intensity does not have to be incredibly powerful to create these microconductors. These lines can be used as conductive paths for component interconnection. This possibility will be investigated in the next section. The intent here is to illustrate its applicability to microcircuits. Similar things may be said of extrinsic photoconductivity.
Fig. 14  a) Intrinsic photoconductivity production;  
b) Carrier sheet and diffusion profile.
Chapter II is a specific example of extrinsic photoconductivity. It involves the photo-excitation of carriers from or to levels in the bandgap\(^3\). This process is shown in Fig. 15. It allows for the generation of single carriers, either electrons or holes in specified areas depending on the doping. These activated regions may be applied as in the intrinsic case. This is examined in the next section.

3.2 Additional Examples

As shown in Chapter II on p to n inversion, the optical techniques allow control over geometry and carrier densities. Therefore, proper masks allow creation of conduction areas according to the patterns projected. This ability allows the fabrication of conductors, resistors, and various active devices. In addition to the p-n inversion case the more common intrinsic and extrinsic photoconductive phenomena may also be used to make some essential components. However, these processes cannot be used for bipolar devices due to their nature. The devices must be of a field effect type. This property may motivate some active structures, as shown in Fig. 16. The first is similar to a FET in that a positive voltage will attract electrons into the channel from the square bulk while negative depletes it. The second is a punch-through type device. (Both may be done in the p-n inversion case as well.) When the gate has the correct voltage, break-down may occur at both junctions giving direct communication between the two contacts. These are very hypothetical structures indeed. Both are based on extrinsic phenomena but may extend to intrinsic.
Fig. 15 Extrinsic photoconductivity production
Fig. 16  a) Extrinsic field effect gate;  
b) Punch-through gate.
Fig. 17 a) Intrinsic passive components;  
b) Extrinsic passive components.
Passive components may be made using both types of photoconductivity. These are shown in Fig. 17. Some other important components become necessary for integrated circuits.

Crossovers are essential for the implementation of nonplanar circuits. These may be formed using intrinsic photoconductivity. Figure 18a illustrates this possibility. The crossover is initiated because of the high attenuation of the light and the sheet nature of the carriers produced.

Intrinsic photoconductivity may also be used to form ohmic contacts between metals and the crystal itself. The incident light produces enough electrons and holes in the vicinity of the metal contact to form the connection. The ohmic contact is shown in Fig. 18b.

It can thus be seen that other forms of photoconductivity may be applied to microcircuitry as desired. Chapter IV briefly describes integrated circuit applications and others of an even more hypothetical nature.
Fig. 18  a) Electrical crossover;  b) Optically produced ohmic contact with metal
IV. PROPOSALS FOR FURTHER STUDY

In previous sections the feasibility of p to n inversion has been demonstrated. This technique has been applied toward the possible formation of the usual bipolar elements. Also other photoconductive effects have been examined and applied to component application. This concluding chapter will explore the use of this optical technique in integrated circuit applications as well as other interesting situations. The advantages and disadvantages of this technique are also briefly weighed. Finally a summary of the thesis is given which outlines some possible avenues of future study.

4.1 Possible Applications

A natural extension of the previous development is the integrated circuit. The only actual hardware required is a crystal substrate uniformly doped, a light source, and a light filter mask. Thus the creation of a specified circuit is reduced to the construction of a blocking mask defining the components and interconnections. A possible system configuration is shown in Fig. 19. The substrate will have metal fingers about its perimeter for electrical communication with the external world. Such a system would be ideal for testing circuit designs. If the masks were interchangeable, the system would be completely configurable according to the masks applied.

This system is not an IC in the usual sense, (DIP package). Instead the semiconductor is a fixed part of the entire system. This presents some distinct differences in the production process of circuits. The production process for diffused technology circuits is
Fig. 19 Integrated circuit system
Fig. 20  Normal IC production flow chart (basic)
given in Fig. 20 while the optical production technique is given in Fig. 21(5). Their comparison illustrates some possible advantages and disadvantages. Wafer preparation offers the advantage in the optical case of not needing an epitaxial layer. Also all of the active dopants are added in the crucible for the optical case while the diffused IC requires the implant of dopants using several steps, this is a distinct advantage. The number of required masks for the optical technique is less than the diffused thereby reducing complexity. The reduction of complexity improves yield and thus reduces testing requirements, lowering cost. Some disadvantages exist due to the light source. It requires power and space creating a cost increase. The extra bulk restricts many application areas. A further disadvantage is a loss in density from optical resolution limitations. This however may be countered by the fact that the wafer may be many times larger than a conventional chip (~1cm²). These production advantages together with the application advantages provide some impetus to develop this technique.

Another potentially interesting application would be the ability to create active structures by means of a 3-dimensional intersection of projected light(11). This is possible since the inversion process is dependent upon the light intensity. Single beams may not be strong enough to create inversion, but intersected beams may be constructively intense enough to cause inversion. Thus 3-d structures may be possible within a cube of activated semiconductor. Figure 22 illustrates this possibility.
Fig. 21 Optical IC production flow diagram (basic)
Fig. 22  3-D activated region
Fig. 23. a) Combined diffusion-optical technology, Photo-PROM; b) LED programmable substrate
More possibilities exist when the combination of diffused and optical techniques are considered. Perhaps a photo-PROM in which the interchangeable blocking mask serves as the memory fuse links (Fig. 23a), or a system in which the light source is controllable directly as in Fig. 23b(12). The circuit can be changed by changing the LED array.

Indeed many possibilities exist for this optical technique. The final section is a brief summary of some possible areas of future study.

4.2 Summary

This thesis has shown the feasibility that a crystal doped appropriately can be optically inverted from p-type to n-type at room temperature. It has also presented some possible applications and advantages. Clearly this is a highly specific example. Perhaps similar phenomena exist at low temperatures or with different doping combinations. Perhaps different optical techniques or combined techniques can be shown to produce useful circuitry. This thesis is more a proposal than a complete study. The need for further development is obvious from the rather qualitative and ideal treatment here.

Further study may take several paths, perhaps as follows:

Step 1) In depth theoretical analysis of the concept and other possible methods and materials which create similar useful phenomena (shallow impurities at low T, surface states as defects).

Step 2) Extensive experimentation and technique refinement.

Step 3) Applications research to determine the scope and limitations of the developed concept.
Step 4) Technological development for devices and further applications (i.e., erasable blocking masks, pulsed lasers to reduce optical power).

It appears from this thesis that the concept presented is feasible and can offer some interesting applications and advantages. Perhaps with research and development the projected technology from this concept could become a reality.
REFERENCES


11. Conversations with Dr. Burton.

12. Suggestions of Dr. Burton.


Appendix A  Feasibility Range Program

The following program was used to generate Table 3.

10 LET SN = variable
20 LET SP = variable
30 LET SL = variable
40 LET PO = variable
50 LET NO = variable
60 LET ED = .57+.026*LN(PO/1E19)
70 LET F1 = EXP(-40*ED)
80 LET ND = (NO-PO/2)/(.57*F1)
90 LET NA = PO-NO+ND*(2-F1)
100 LET I = 1E7*SN*NO/SL/(F1-PO/ND)
110 LET P = .88E-19*I
120 LET F2 = F1/2-PO/2/ND
130 LET PF = 6.2E15*SP*ND/(5E6*SP*ND*F2+1E3)
140 LET NF = (PF+2*ND-NA)*SL*I/(SL*I+SN*ND*5E6)
150 PRINT ND,NA,P,NF,PF

This program uses x = 2 and $V_n = 5E6 (5 \times 10^6 \text{cm/sec})$. These and the other parameters may be varied over different ranges to illustrate feasibility regions. A small portion of such a variation is given in Table 3 for $T = 300^\circ \text{K}$ (T may also be varied.).
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ON THE FEASIBILITY AND APPLICATION OF OPTICAL P TO N

by

Eric D. Cole

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(ABSTRACT)

The feasibility of achieving carrier inversion of a properly doped crystal via optical excitation is studied. This process involves a host substrate doped with deep donors for n-type light characteristic and compensated by a shallow acceptor for p-type characteristic in the dark. This substrate is analyzed using well-known semiconductor equations. In addition conditions which must exist for carrier inversion are also specified. The solutions found are applied to a realistic set of dopants for illustrative purposes as well as indication of feasibility range. This inversion technique may possibly be used to generate bipolar junctions and thus devices. Other forms of photoconductivity are also qualitatively considered to supplement and extend the range of the inversion techniques applications. The processing of circuits using the developed concept offers possible interesting and useful advantages over existing techniques. The motivation for further research thus becomes obvious and is indeed the purpose of the thesis.