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# Near Contact Phenomena and Transient Effects in Far Infrared Photoconductors

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**Abstract**

This presentation summarizes a combination of experimental and modeling work in two areas: first, the calculation of excess free carrier and space charge distributions near contacts and their effects on device resistivity, and second, the characterization of a slow transient response ($\tau \sim 1$ sec) in Ge:Be detectors which is due to trapping associated with $Be^+$ formation. In both cases, analytical models, based on continuity and rate equations, have been developed to enable the application of these findings to a wide variety of photoconductor materials.

## I. Near-contact Behavior

The goal of this work was to model the distribution of excess free carriers and space charge in the bulk material immediately adjacent to a heavily doped contact region. Figure 1 shows schematically the distribution of free holes (p), ionized acceptors ($N_A^-$), electric field (E) and potential (V) that might be expected as a result of the diffusion of carriers due to the concentration gradient and the resultant space charge. The object of the modeling was to determine the exact extent and shape of the space charge region, as a function of material parameters such as doping, compensation and mobility. Several attempts have previously been made to solve this problem using numerical modeling, but diffusion in both cases was neglected in the space charge region (1,2). This is not a good assumption, because the diffusion current plays a significant role in the near-contact region.

A complete numerical solution, including both diffusion and drift components to the current, has recently been completed (3), and this presentation is a summary of that work. Readers are referred to the publication for a complete discussion of the problem. The distributions of free holes ( for p-type material), ionized acceptors and electric field are calculated by combining the continuity equation, Poisson's equation and the current equation. The continuity equation, for the steady state, can be expressed as



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$$\mu p E' + \mu p' E + D p'' = 0 \quad (1)$$

where $\mu$ is the mobility of the free carriers, D is the diffusion coefficient and the derivatives represent spatial derivatives in one dimension. Since Poisson's equation and the current equation can be used to express E and E' as a function of p, the final equation to be solved is a second order differential equation in p. This has been solved using a finite difference technique (4). In this work, we have used low field approximations and have not included the dependence of capture cross section on electric field or the effects of velocity saturation. These are valid assumptions for the low fields at which Ge detectors are usually operated.

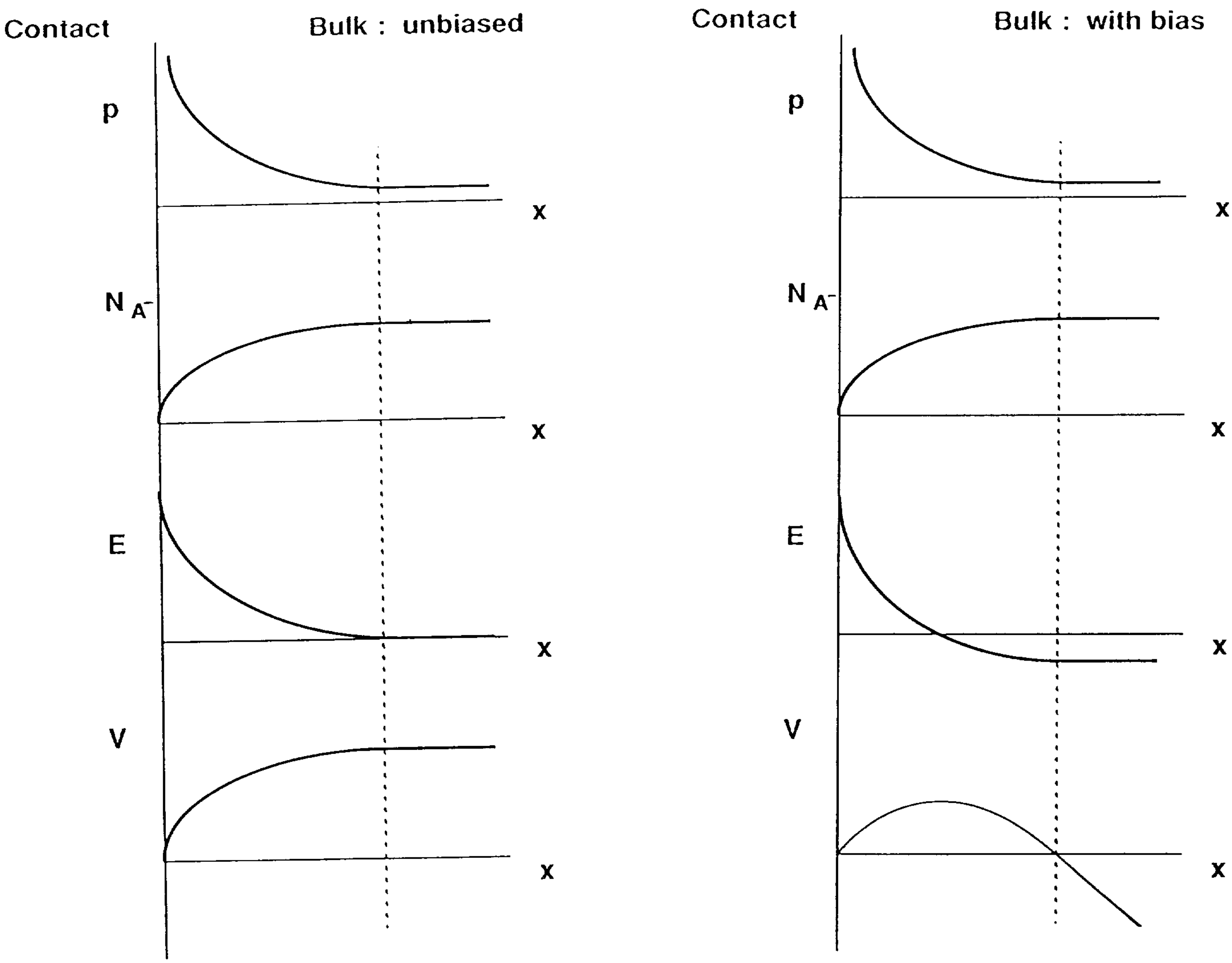
The modeling parameters for this work are those appropriate for p-type Ge:Ga photoconductors operated under low photon backgrounds at 3.0 K. The boundary condition on both sides was taken as a thin region (L = 0.25 μm) with an excess hole concentration of $10^{16}$-$10^{18}$ $cm^{-3}$.

Solutions as a function of device thickness are shown in Figure 2 for a 10 μm and 25 μm thick layer of material with a contact at either side. In Figure 3, the effect of bias, on a 100 μm thick layer, is shown. The results are for material with a Ga concentration of $2 \times 10^{14}$ $cm^{-3}$, with a compensating donor concentration of $10^{11}$ $cm^{-3}$. One sees that for the very thin layers, the resistivity of the device would be dominated by contact effects, since the hole concentration is determined by diffusion from the contact. Bulk resistivity values would not be obtained in an I-V measurement of this type of structure. For the common thicknesses for current detectors, however, ($t \geq 0.5$ mm) the contact should not have a significant effect on the I-V characteristic.

In Figure 4, the effect of varying the compensating donor concentration is seen. The space charge region will extend much farther as the compensation ratio is decreased. Thus, one would predict a contact effect on measured resistivity for thickness less than 200 μm for lightly compensated material with $N_D = 10$ $cm^{-3}$. The critical thicknesses will be even less for donor concentrations in the ranges of $10^{11}$-$10^{12}$ $cm^{-3}$, which are more common for Ge:Ga.

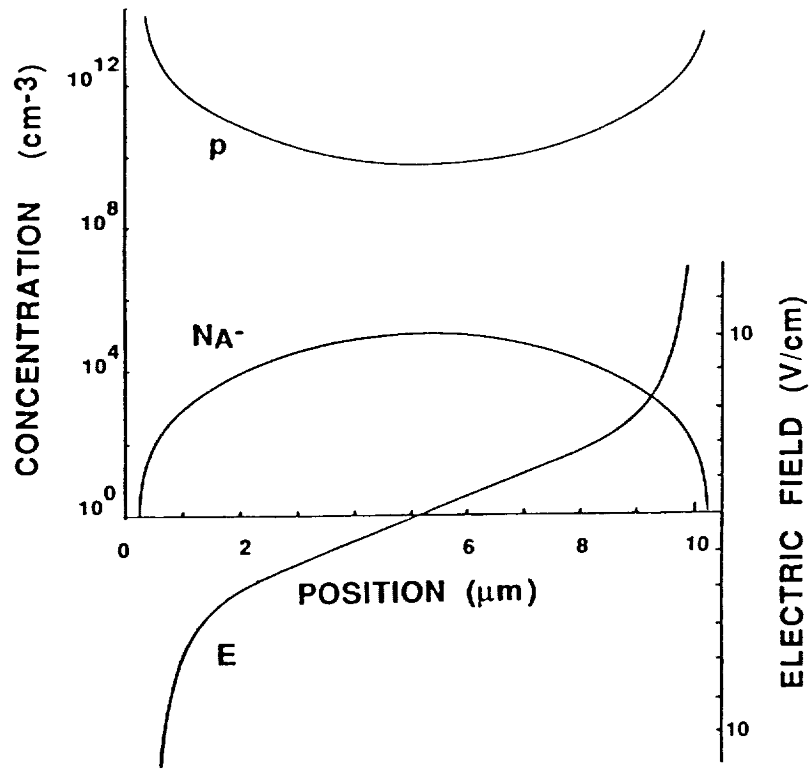
We have developed analytical expressions for the extent of the space charge region and the excess carrier concentrations and have verified them with the numerical results. These expressions are given in Figure 5. With these results, one can determine the effect of the contact in any extrinsic photoconductor.

The calculation of the steady state space charge distributions near the contacts is a necessary first step for further investigation of the transient response of the space charge region. Experimental work is in progress in order to verify the modeling predictions. We will measure the I-V characteristics and study the fundamental transport behavior of thin devices in the contact-dominated regime.

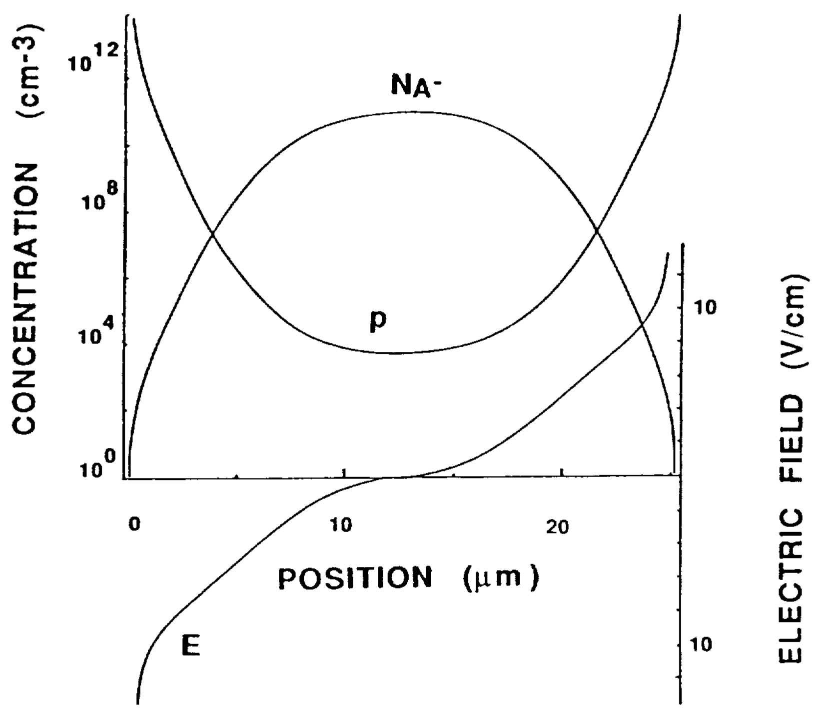


Contact
Bulk : unbiased
p
x
N A-
x
E
x
V
x
Contact
Bulk : with bias
p
x
N A-
x
E
x
V
x


Figure 1

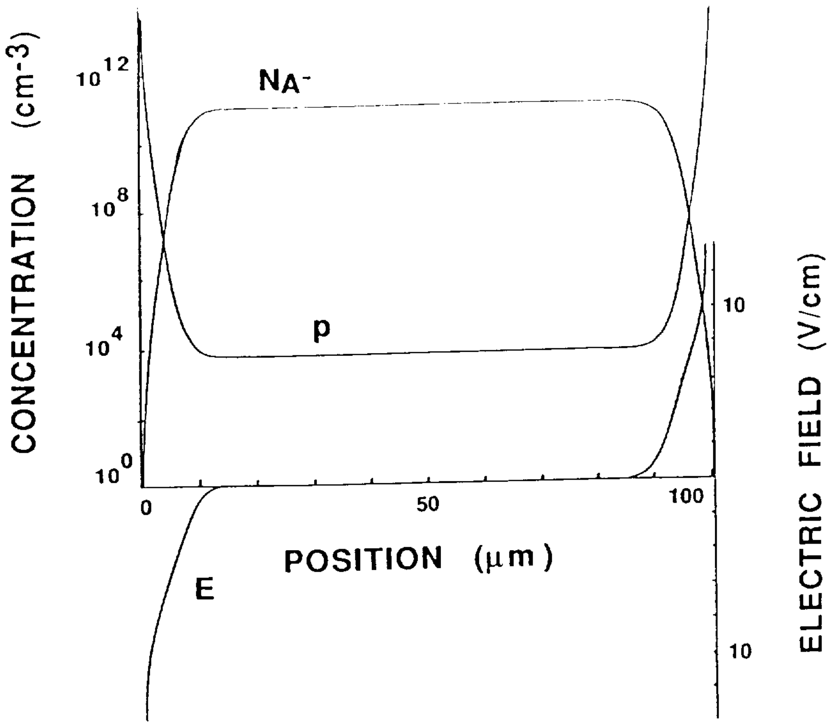


CONCENTRATION (cm-3)
10^12
10^8
10^4
10^0
p
NA-
E
0
2
6
8
10
POSITION (µm)
ELECTRIC FIELD (V/cm)
10
10

CONCENTRATION (cm-3)
10^12
10^8
10^4
10^0
NA-
p
E
0
10
20
POSITION (µm)
ELECTRIC FIELD (V/cm)
10
10


Figure 2


CONCENTRATION (cm-3)
10^12
10^8
10^4
10^0
NA-
p
0
50
100
POSITION (μm)
E
10
10
ELECTRIC FIELD (V/cm)

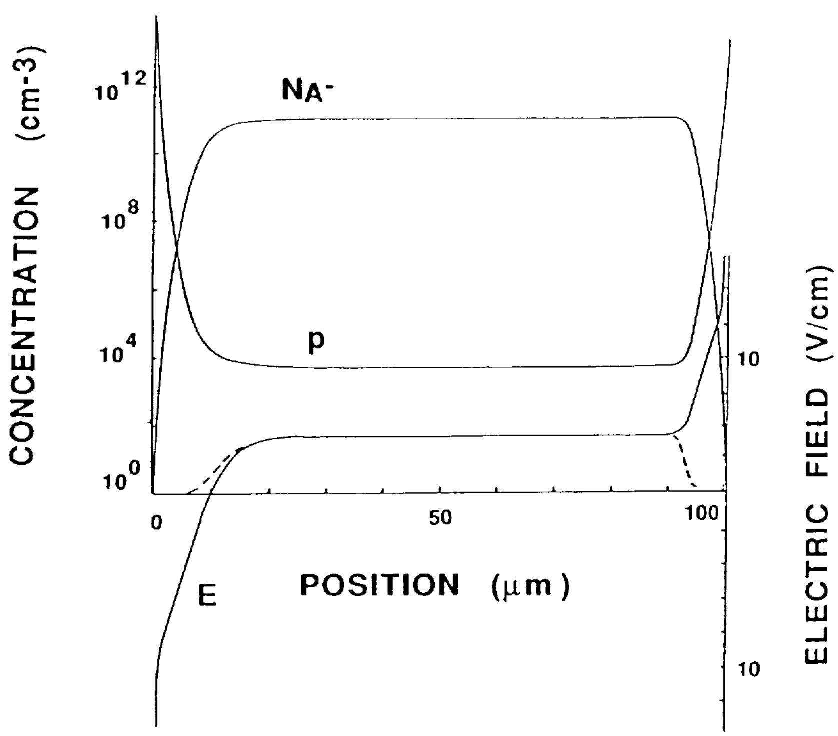

CONCENTRATION (cm-3)
10^12
10^8
10^4
10^0
NA-
p
0
50
100
POSITION (μm)
E
10
10
ELECTRIC FIELD (V/cm)

Figure 3

(a) $N_D = 10^{12}\ cm^{-3}$

(b) $N_D = 10^{11}\ cm^{-3}$

(c) $N_D = 10^{10}\ cm^{-3}$

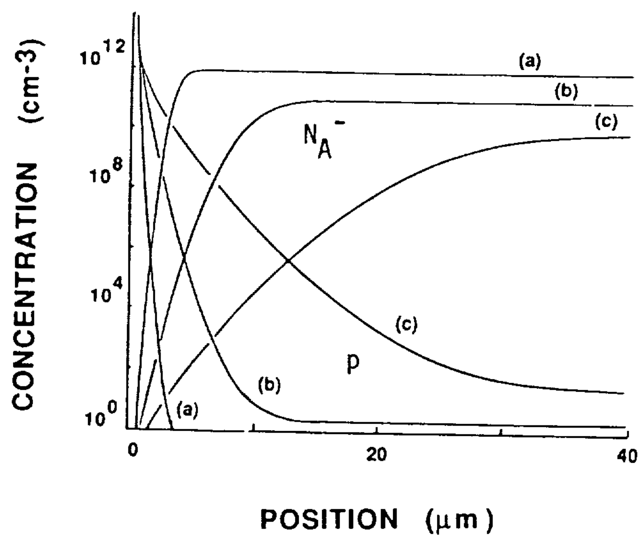
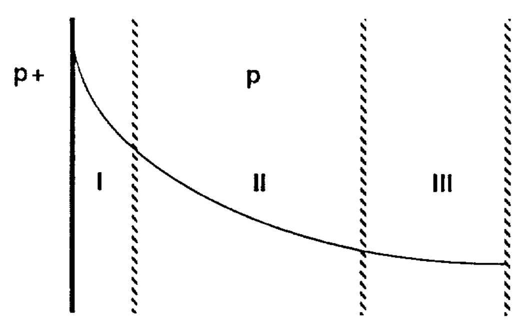



Figure 4

General Analytical Solutions: Si:X, GaAs:X, . . .




Distance of zones

I. $\Delta x = \lambda_i\left(\sqrt{\frac{N_{imp}}{10\, N_D}} - 1\right)$

II. $\Delta x = \sqrt{\frac{2\varepsilon_s V}{e\, N_d}}$ $\qquad V = \frac{\varepsilon_A}{e} + kT\, \ell n\left(\frac{N_D^2}{N_v N_A}\right)$

III. $\Delta x = \sqrt{\frac{2kT\varepsilon_s}{e^2 N_D}}$

Figure 5

## II. Transient Phenomenon due to $A^+$ Formation in Ge:Be Photoconductors

A slow transient response to step function increases in photon flux, with a time constant on the order of 0.1 - 1.0 sec, has previously been identified and documented in Ge:Be photoconductors operation under low photon backgrounds at temperatures of 2-3 K (5). A combination of modeling and experimental work has shown that the transient response is due to the effect of the formation of the overcharged Be acceptor center $Be^+$. This presentation summarizes a study of this phenomenon which has recently been published (6), and the reader should consult this reference for a complete description of the work.

The photoconductive response to a step function in photon signal as a function of temperature is shown in Figure 6. The transient response has a time constant which is significantly longer than would be expected due to either the free carrier lifetime or the dielectric relaxation time in the material. We believe that the slow transient response is due to hole trapping by neutral Be atoms to form the overcharged acceptor $Be^+$. Be can bind three or even four holes because of the four-fold degeneracy of the top of the valence band, and the existence of $Be^+$ has been clearly established experimentally (7).

The mechanism for the trapping phenomenon is shown in Figure 7. Development of the rate equations for the process results in an equation for the time constant $\tau'$ associated with $Be^+$ trapping and equilibration of

$$\tau' = \tau_o \left[ \frac{Be}{Nv} e^{E/kT} \right] \quad (2)$$

where $\tau^o$ is the free carrier lifetime, Be is the Be concentration, $N_v$ is the valence band density of states and E is the $Be^+$ binding energy.

A plot of $[\tau'/\tau^o \times T^{3/2}]$ will have a slope proportional to the binding energy of the $Be^+$ center. This is shown in Figure 8. The value of 4.3 meV which is obtained from the data is in excellent agreement with the 4.5 meV binding energy of $Be^+$. The application of uniaxial stress, which breaks the degeneracy of the top of the valence band and eliminates $Be^+$ formation, also eliminates the slow transient response, as shown in Figure 9. This gives additional support to the assignment of the mechanism as associated with $Be^+$ formation.

Equation 2 can be adapted and used to estimate the time constant for $A^+$ or $D^-$ trapping in any photoconductor material as a function of temperature. Overcharged acceptor and donor centers have been identified in a variety of photoconductor materials, including Ge:Ga, Ge:Be, Si:P, Si:B and Si:As.

In summary, a slow transient response, with a time constant on the order of 0.1 to 1.0 sec. between 2 and 3 K, has been observed in the photocurrent of Ge:Be extrinsic photoconductors. The activation energy of the transient phenomenon (4.3 meV) and its behavior under applied uniaxial stress indicate that trapping due to the formation of $Be^+$ centers is responsible for the dynamics of the photoresponse. An analytical model of transient photoconductivity in a unipolar system, where the trapping mechanism is associated with $Be^o \rightarrow Be^+$, gives good agreement with the experimental results.

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Acknowledgements


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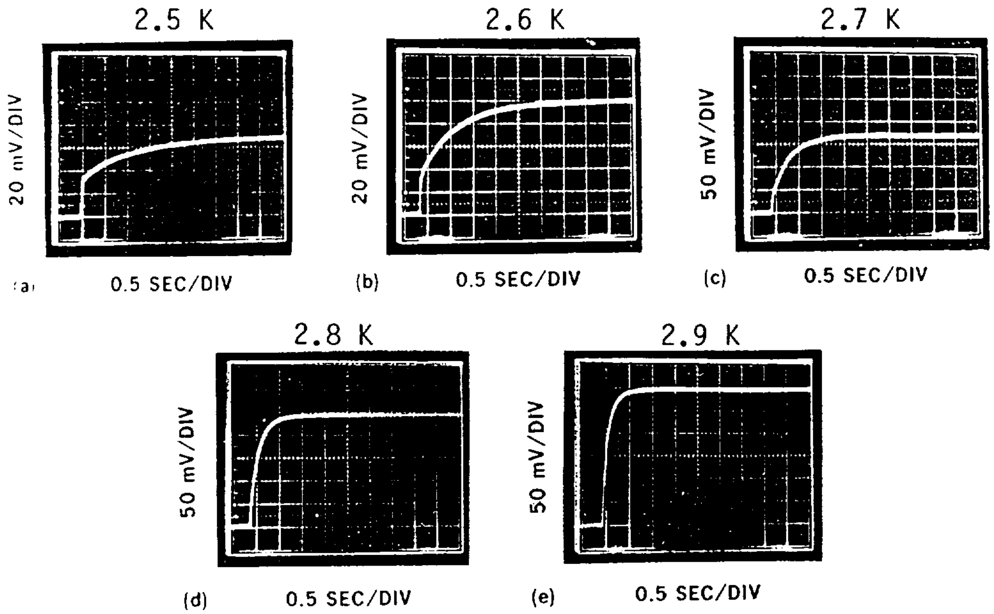


Figure 6

## PROPOSED MECHANISM:

## Hole trapping by $Be^{o}$ to form $Be^{+}$

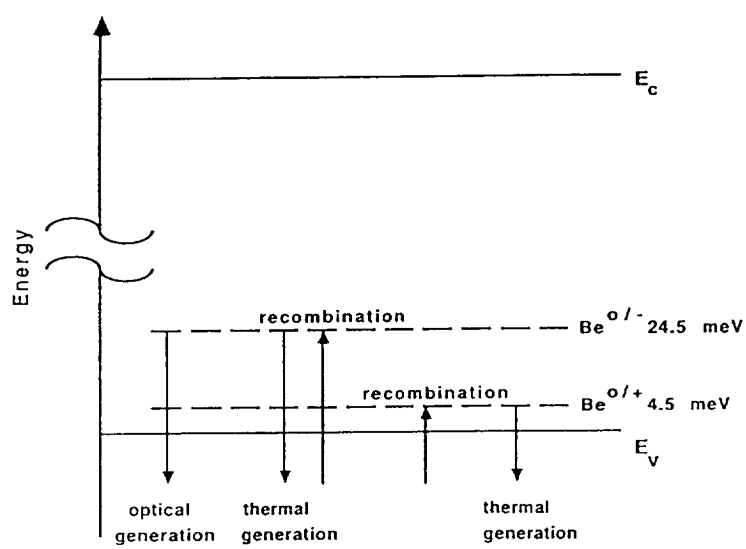


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Figure 7

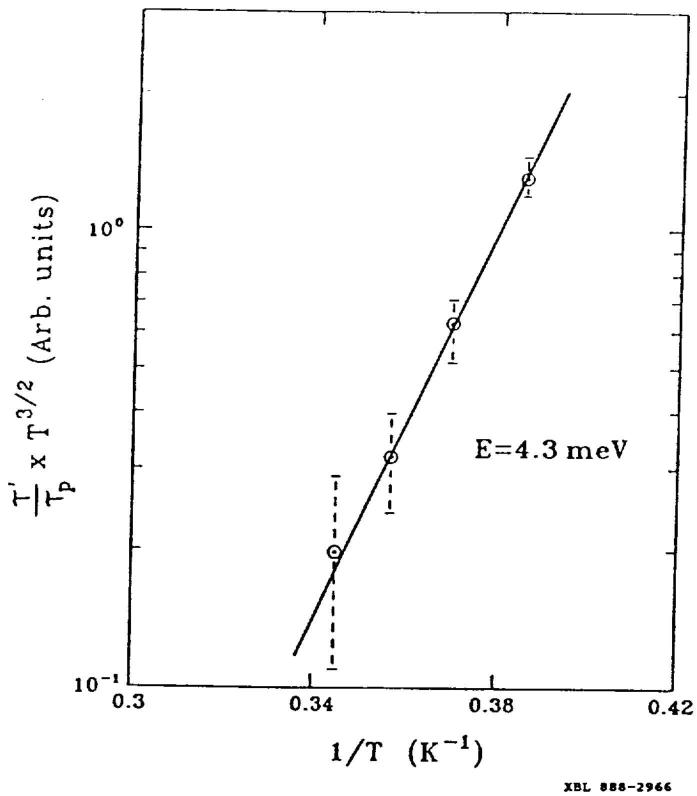


Figure 8

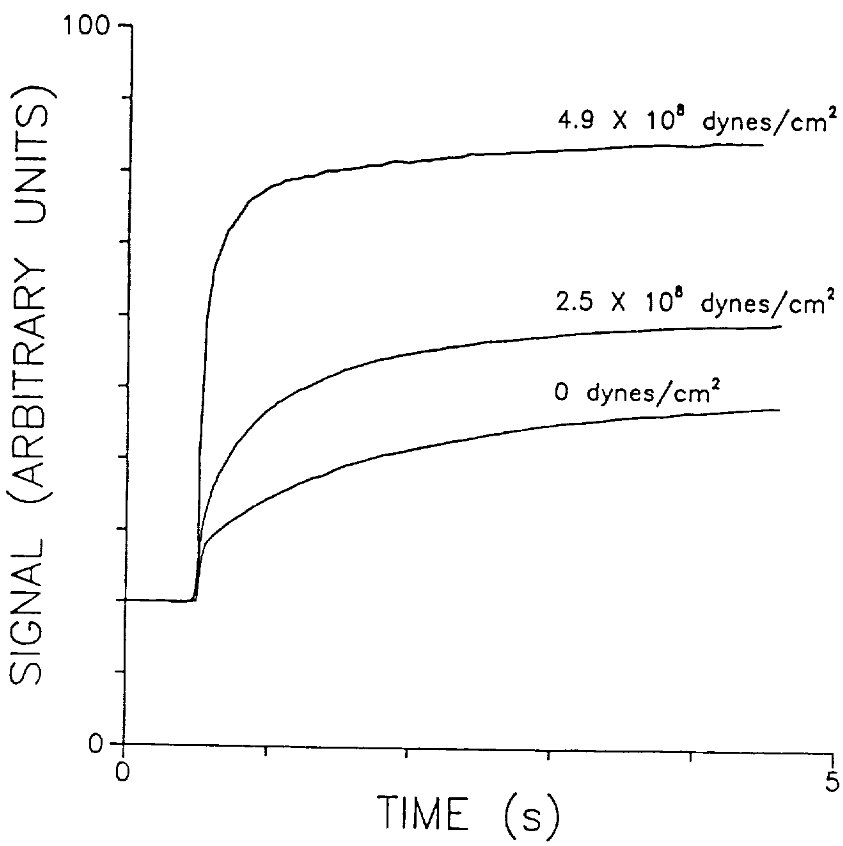


Figure 9