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A study of the kinetics of light induced modulation of absorption in zinc selenide

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A STUDY OF THE KINETICS OF LIGHT INDUCED MODULATION OF ABSORPTION IN ZINC SELENIDE

BY

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III. ABSTRACT

Light Induced Modulation of Absorption, or LIMA, was discovered by E. J. Conway in cadmium sulfide in 1967. It holds promise as a non-destructive test for material defect analysis. In 1969, R. W. Major began studying LIMA in zinc selenide. This paper is an extension of his research and findings.

The physical phenomenon of interest is optical absorption. ZnSe has a characteristic band gap of 2.7 ev with an equivalent wavelength of 4770 Å. Two light beams at longer wavelengths are passed through a ZnSe crystal, a low intensity monochromatic light and a higher intensity laser beam which modulates the former. Data are taken in the form of recorder charts showing changes in modulation of the former at various wavelengths by the latter versus time.

Of primary interest is the role of impurities in the sample. Similarities and differences are drawn from previous work done by Major and D. E. Everett, with the same crystal used by the author, and from work by Stringfellow and Bube in ZnSe containing copper as the main impurity. Conway has recently proposed a model for CdS to explain why LIMA does not immediately begin to decay upon laser shut-off. This will be discussed in trying to describe electron-hole recombination kinetics.

The author was able to gain a better understanding regarding LIMA than in previous work. A narrower gate yielded improved time resolution of data, and a better interpretation of data followed. Further work

should be focused on longer wavelengths and longer times between laser pulses in order to better delineate decay kinetics. Studies should also be made at lower temperatures in an attempt to explain a possible modulation component arising from laser heating of the sample.

IV. INTRODUCTION

The band gap of zinc selenide (ZnSe) is about 2.7 ev at room temperature, corresponding to 4770 Å. When transmitted through a ZnSe crystal, a low intensity monochromatic light exhibits a definite absorption coefficient for each wavelength having associated energy less than the gap energy.

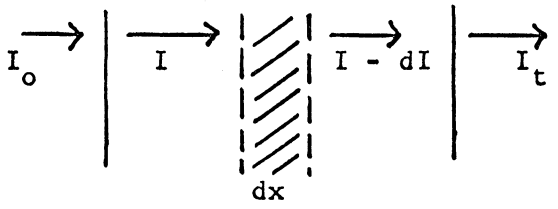
One way of changing the absorption coefficient is by simultaneous absorption of high intensity photons. If the energy of these photons exceeds the characteristic band gap, then the electrons in the valence band can absorb enough energy to cross the band gap directly. But this approach will reveal little or nothing about the role of energy levels within the gap. If the crystal were pure, then no energy levels could exist within the gap. Any photons with energy less than the gap energy could not be absorbed, and the transmission of monochromatic primary light would be unaffected. But no perfect crystal exists; there are often energy levels within the gap which affect this absorption, most likely impurities.

One technique for changing the absorption coefficient is the effect, which is the basis for the work reported here, called Light Induced Modulation of Absorption, or LIMA. It was discovered by E. J. Conway[1], at NASA-Langley, in cadmium sulfide (CdS), perhaps the best-studied representative of the II-VI semiconductors.

Conway used photons from two different lasers, one of 5308 Å and the other of 6471 Å, in studying CdS, which has a band gap of 2.42 ev, corresponding to 5127 Å. He found, in studying wavelengths from 5000 Å to 20,000 Å for several CdS crystals, one region of decreased absorption, from just below the absorption edge to about 5800-7000 Å depending on the crystal. Longer wavelengths showed increased absorption. The magnitude of change in optical absorption, $\Delta\alpha$, was strongly dependent upon laser intensity. In the former, $\Delta\alpha$ varied linearly as laser intensity and sublinearly in the latter. This indicated "the transition between monomolecular and bimolecular recombination kinetics."[2] $\Delta\alpha$ was found to be negative at wavelengths near the absorption edge and positive for longer wavelengths. The transition wavelength, where $\Delta\alpha$ crosses from negative to positive, was unique to each crystal and independent of laser intensity.

In 1969, R. W. Major, the author's advisor, began studying LIMA in another II-VI compound, zinc selenide. The purpose of this paper is twofold. One is to report developments in this work in ZnSe. Earlier work by Major and D. E. Everett has shown the effect to be reproducible - even with a laser 1000 times less powerful than the laser Conway used. This work was concentrated in studying rise kinetics with time bases as short as 1 ms for a 2.5 ms laser pulse. The work reported here was concentrated on the signal kinetics with emphasis on decay at a series of wavelengths just below the fundamental edge (4800 to 5300 Å). The second purpose is to try to construct a model which will be consistent with the results of these data. Later in this section, two possible models will be examined to show possible electron-hole recombination kinetics.

Before any theory is discussed, an explanation should be given of what is being measured, the change in the absorption coefficient α versus time for each wavelength. Conway used the simplified equation $\Delta\alpha = -x^{-1}(\Delta I_t/I_t)$ to present his results, where x is crystal thickness, I_t is transmitted intensity, and ΔI_t is the change in transmitted intensity. Consider a small cross-section of a crystal composed of homogeneous material implying constant α:



$$\text{or } (I - dI) - I = \alpha I dx$$

$$-dI = \alpha I dx$$

$$dI/I = -\alpha dx.$$

Thus for the whole crystal thickness, $(I_t - I_o)/I_t = -\alpha x$. This approximation is possible since αx is of the order of 10^{-1} where x is about 0.1 cm and α is less than 10 cm^{-1}.

Consider two different states of the crystal for the same wavelength characterized by α_1, laser off, and α_2, laser on: For α_1

$$(I_{t1} - I_o)/I_{t1} = -\alpha_1 x$$

$$\alpha_1 = -x^{-1}(I_{t1} - I_o)/I_{t1}$$

$$\Longrightarrow \alpha_2 = -x^{-1}(I_{t2} - I_o)/I_{t2}.$$

Assume that $I_{t1} + \Delta = I_{t2} \approx I_{t1}$. This condition is met experimentally in that the ratio is about 1 part in 10^3, or 0.1 %. Therefore

$$(\alpha_2 - \alpha_1) = -x^{-1}\,(I_{t2} - I_o)/I_{t2} - (I_{t1} - I_o)/I_{t1}$$

$$\Delta\alpha = -x^{-1}(I_{t2} - I_{t1})/I_t$$

$$\Delta\alpha = -x^{-1}(\Delta I_t/I_t).$$

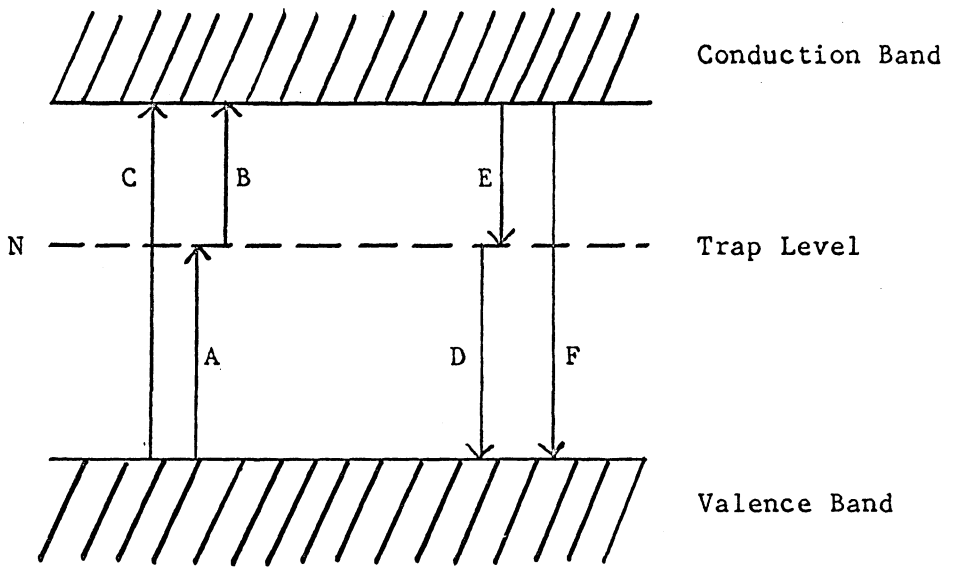
The changes in transmitted intensity activate a photomultiplier tube. The output voltage from the PM tube at any given wavelength is assumed to vary linearly with transmitted intensity I_t; that is, $I_t = kV$, then $\Delta I_t = k\Delta V$, and $\Delta\alpha = -x^{-1}(\Delta V/V)$.

The laser used here produces photons of 6328 Å, having energy of 1.96 ev, which cannot cause electrons to jump the 2.7 ev gap. The thermal energy at room temperature is of the order of 0.026 ev which is negligible when compared to the laser energy. Comments will be made later concerning laser heating of the sample. The ability to modulate absorption with such a laser photon energy suggests there must be participating energy levels due to impurities and/or imperfections lying in the gap. A look at possible processes may clarify the role of, and possibly identify, these levels. The main processes of interest involve a time rate of change in the electron and/or hole concentrations.

In discussing possible models for LIMA, only models with impurities will be examined since nothing has been found to show that LIMA is caused by other defects within the gap. The simplest theoretical model that can be examined will contain one trap level (i.e. one energy level within the band gap which aids in the redistribution of electrons between the valence and conduction bands). Thermal effects or mechanical vibrations are not considered. This trap may be neutral or positively or negatively charged. For example, there may be an impurity atom such as copper which will give up an electron as it is ionized when it replaces a zinc atom in the lattice. The copper atom is then singly positively charged.

Figure 1 shows the possible transitions that can occur within the band gap with one trap level. The photons from the laser interact with the monochromatic light via population changes in the trap level to cause a change in the absorption of the latter.

Figure 1. POSSIBLE ELECTRON TRANSITIONS IN A SEMICONDUCTOR WITH ONE TYPE OF TRAP (Ryvkin).



Transitions A, B, and C can occur when light from the laser intersects the monochromatic light

Transitions D, E, and F can lead to recombination and are accompanied by the emission of optical energy

In studying CdS, Conway noted a transfer from monomolecular to bimolecular recombination kinetics depending on the range of wavelengths being absorbed. The main difference is that, in monomolecular recombination, electrons recombine directly with holes in the valence band after having come from the conduction band. Bimolecular recombination involves electrons from the host substance recombining via an impurity in the band gap.

Kittel[3] offers a good treatment in the area of photoconductivity - "the increase in electrical conductivity of an insulating crystal caused by radiation incident on the crystal"[4] - to enlighten us on the recombination kinetics. Upon illumination the number of mobile charge carriers increases; that is, electron-hole pairs are created which will recombine after the illumination is shut-off.

For monomolecular recombination, the change in electron concentration is L (the energy absorbed per unit volume per unit time) less the recombination rate Anp (where A is a proportionality constant), proportional to the product of electron and hole concentrations, n and p respectively. For the simple case where n = p, then $dn/dt = L - Anp = L - An^2$. Since the effect of laser photon absorption in the crystal is to generate electron-hole pairs, this case could be valid in the present work. To find what the decay should look like, solve the above for L = 0 where n_o is the electron concentration at t = 0. $dn/dt = -An^2$ yields $n = n_o/(1 + Atn_o)$. If $Atn_o \gg 1$, then $n = 1/At$ or $n \propto 1/t$. A graph of this is a series of curves of the form nt = k for any constant k. Note that the steady state shows, for dn/dt = 0: $L = An^2$, or $n^2 = L/A$. Thus $n \propto L^{\frac{1}{2}}$.

To look at bimolecular recombination, again use the above relationship, this time substituting n+N for p where N is the trap level density,

or $dn/dt = L - An(n+N)$. In the steady state, $L = An(n+N)$. There are two limiting cases, $n \ll N$ and $n \gg N$. In the case where the electron density is much less than the trap level density, $n+N \approx N$ and $L = AnN$ which yields $n = L/AN$. Thus n is directly proportional to L. If, on the other hand, $n \gg N$, or $n+N \approx n$, then $L = An^2$ which yields $n = (L/A)^{\frac{1}{2}}$. In this case where the trap level density is negligible when compared with the electron density, the result approximates that of monomolecular recombination where no traps exist. To consider system decay, solve as before: $dn/dt = -An(n+N)$ which yields $\log\left[(n+N)/n\right] - \log\left[(n_o+N)/n_o\right] = NAt$. In this limiting case where the trap density is much greater than the electron density when illumination is shut off, $n_o \ll N$ implies $n \ll N$ and $n = n_o\exp(-NAt)$. The response time for the signal to decay to 1/e of its initial value is $t_o = (NA)^{-1}$. Such decay kinetics have been compared with decay data for a 5000 Å primary beam by Major.[5] The agreement is not perfect since the latter appears to be composed of two almost-linear portions.

To examine a more complex model, the reader is referred to Ryvkin[6] who treats the model in Figure 1, which includes possible thermal effects. The solution of the resulting equations for the changes in electron, hole, and occupied trap densities requires complex mathematical techniques. Transition C does not apply here since the laser photons of 1.96 ev cannot bring about band-to-band transitions.

A model will be discussed in the last section of this paper after the data have been analyzed and possible suggestions have been considered. For example, a recent proposal by Conway includes three different trap

level types to explain why the rise kinetics continue for a definite time after laser shut-off, and Major has suggested that short-duration thermal effects may be involved.

V. EXPERIMENTAL DESIGN AND INSTRUMENTATION

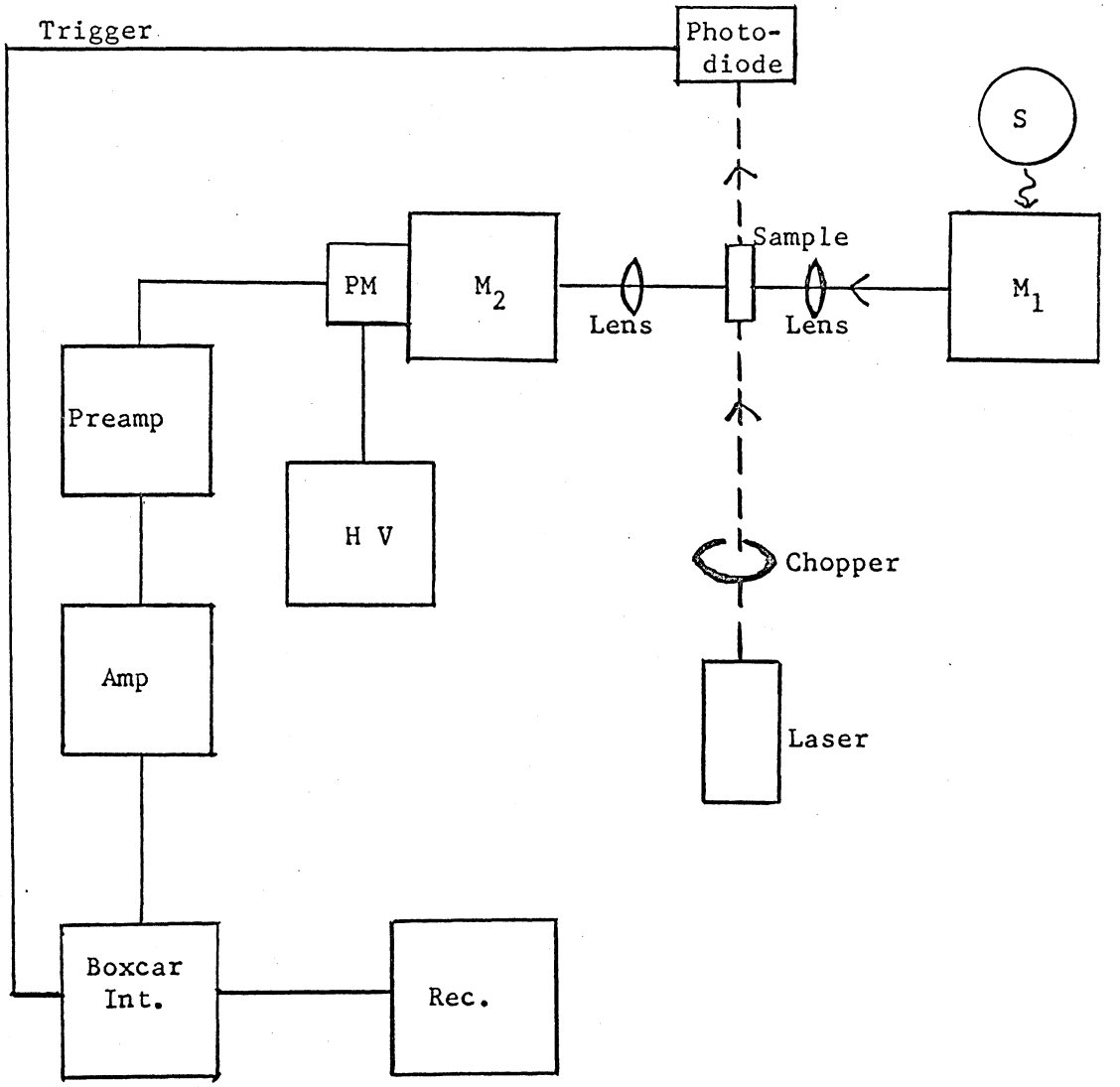
The physical apparatus used to study LIMA in ZnSe is similar to that which Conway used in working with CdS, and consists of three subsystems, the constant-intensity monochromatic source, excitation beam, and detection system with necessary supporting electronics. (See Figure 2)

The source subsystem includes all items necessary to get a monochromatic light to the crystal, namely the primary light, monochrometer, and focusing lenses. A GE 1497 tungsten-filament lamp operated at about 2.75 volts DC is focused through a fixed lens into a Bausch and Lomb grating monochrometer. A second lens is then used to focus the light onto the sample.

The excitation system includes items necessary to cause a change in the monochromatic light: the laser, beam chopper, and ZnSe crystal. A He-Ne continuous-wave laser, Spectra-Physics model 120, emits photons of 6328 Å having energy of 1.96 ev with a flux of about 1.9×10^{16} photons per second. The laser beam is pulsed by a mechanical chopper consisting of a disk with four slits cut in it placed on the shaft of an electric motor which yields an effective pulsing rate of 114 Hz. Considering the power of the laser of 6 mw with a beam diameter of 0.7 mm and a crystal edge of 6.0 mm by 1.5 mm, effectively 4.8×10^{13} photons hit the crystal with each pulse.

The laser beam then passes through the crystal, modulating the primary beam, after which it activates a photodiode, used with the supporting electronics. This is used with the detection system which is the

Figure 2. EXPERIMENTAL ARRANGEMENT.



receiving monochrometer and photomultiplier tube. The supporting electronics include a low-noise preamplifier, amplifier, boxcar integrator, and chart recorder.

After leaving the crystal, the modulated monochromatic beam passes through a collecting lens into a grating monochrometer made by the American Instrument Company and activates an RCA IP-28 photomultiplier tube. This PM tube is designed to operate over a range of 4500-5500 Å at 500-1200 volts DC and is presently operated in the range of 550-600 volts DC in an effort to minimize electronic noise. The tube response for each wavelength is assumed to be linearly proportional to the amount of light activating the tube.

The output signal of the tube is now analyzed by the supporting electronics. Since the AC component is only a few thousandths of a volt, the signal is processed through two stages of amplification. The first is a low-noise, variable-band, solid-state preamplifier, Princeton Applied Research Model CR-4. The second is an AC/DC tube amplifier, Furst Electronics Model 220. The former has been operated with a gain of 10^2 and the latter at 10^1. These two gains can be reversed with little effective change in the unprocessed signal. Although a gain of 10^3 is available on the first-stage amplifier alone, the presence of high noise peaks which overdrive its final stages prevent use of this setting.

The resulting signal of the order of 1 volt AC including noise is then fed into a boxcar integrator, P. A. R. model CW-1, which uses a sampling and averaging technique to extract synchronous wave forms from noise. The principle underlying this is that, if a large number of pulses are examined and averaged, the random noise will be averaged to zero and

the true wave form will survive. The output from the photodiode triggers the integrator to initiate scanning when the laser pulse begins and ends.

The total scan time is that time necessary to extract a signal and depends upon the time constant, time base, signal repetition frequency, and gate width. All that need be said about the time constant is that it is an internal characteristic of the integrator which affects the quality of the final trace. The scan time is proportional to the laser pulse frequency. The time base is the duration of signal being examined, and the gate is that portion of the time base which is being examined at any instant. The gate moves uniformly from beginning to end of the time base in a time corresponding to the scan time. The gate affects both signal resolution and the scan time. The wider the gate, the shorter the scan time and the poorer the resolution, and vice versa. The integrator needs a minimum of one gate width to respond to a step function implying that the first and second gates on the trace must be considered with reservation. The output from the integrator is fed continuously to a Varian model G-11A strip-chart recorder.

A typical run of data involves a gate of 0.2 ms and a scan time of 500 minutes. Considering the chopping frequency of 114 Hz, each gate interval represents the average of about 1.4×10^5 pulses, and the integrator examines over 3.4×10^6 pulses.

VI. PRESENTATION OF DATA

Table I in the appendix summarizes the latest data taken to investigate LIMA in ZnSe. All data were taken under the same conditions, except as follows: Halfway through the runs, the entrance slit on the second monochrometer was widened from 0.20 mm to 0.25 mm, and the optical geometry of the laser incident on the sample was changed slightly. Only one set of data is shown for each wavelength due to their reproducibility.

To obtain data for each wavelength, overlapping runs were made. With a 2.5 ms laser pulse and 8.8 ms between leading edges of pulses, one 5 ms run was made with the integrator triggered by leading edges, and a second 5 ms run was made triggered by trailing edges. The data were reduced using a uniform procedure: Each continuous trace was read, and the values were plotted at 0.1 ms intervals. These values were then divided by the PM output voltage for normalization. The system gain is constant for all signals shown. This differs from the method Everett used where a first run was made with the laser on the sample. Then a second run was made with the laser off the sample, and the difference was plotted. This method was to allow for any synchronous shifts in the system; it was not used here for several reasons. With each run requiring eight to nine hours, any random variation was unlikely to reappear in a later run. A run was made at 5263 Å with the laser off the sample, shown in Figure 11, and is flat within system noise level. Thus, each of the graphs, Figures 3-10, shows an overlapping pair of runs; the overlap within error indicates

Figure 3. SIGNAL AT 4823 Å.

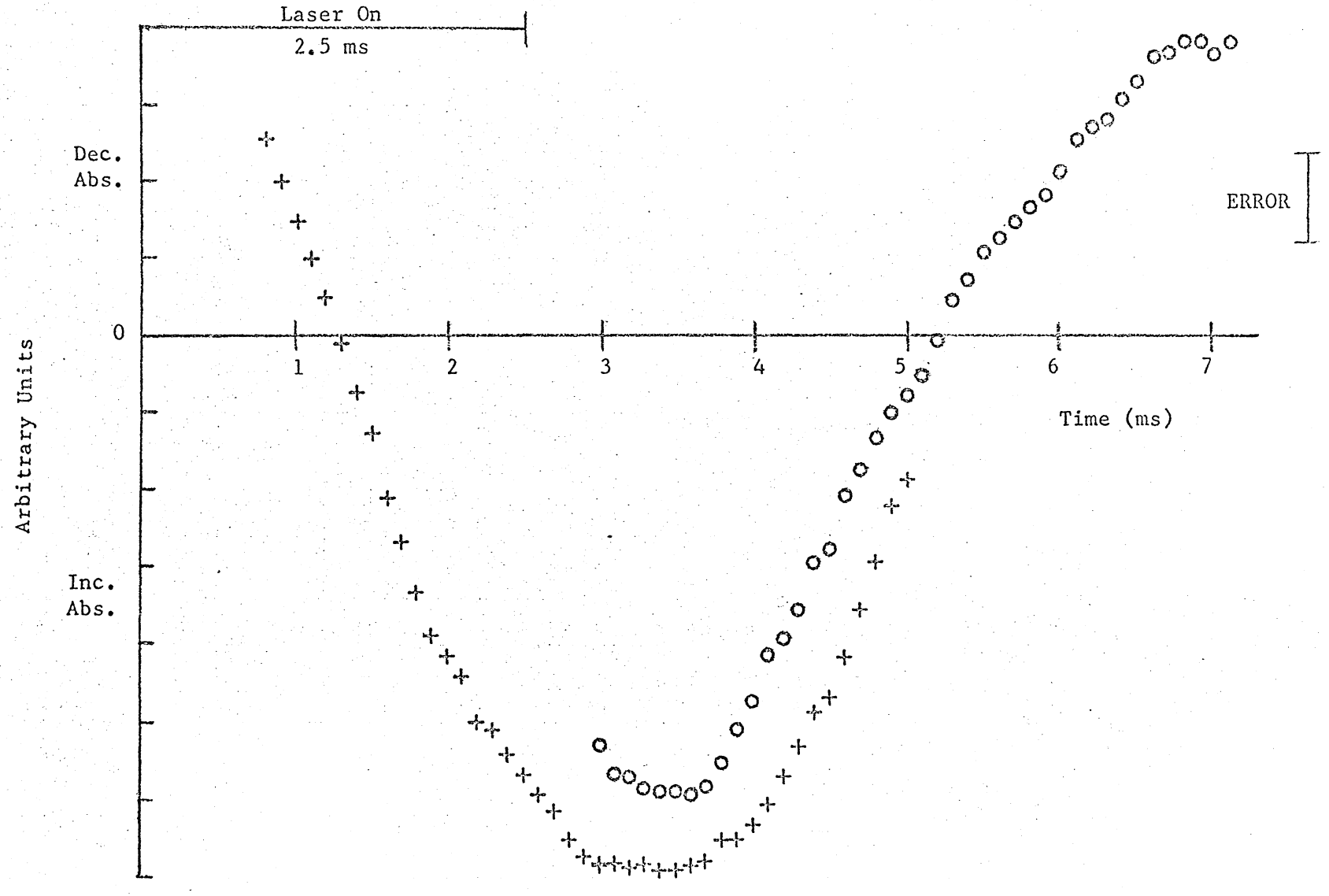


Figure 4. SIGNAL AT 4873 Å.

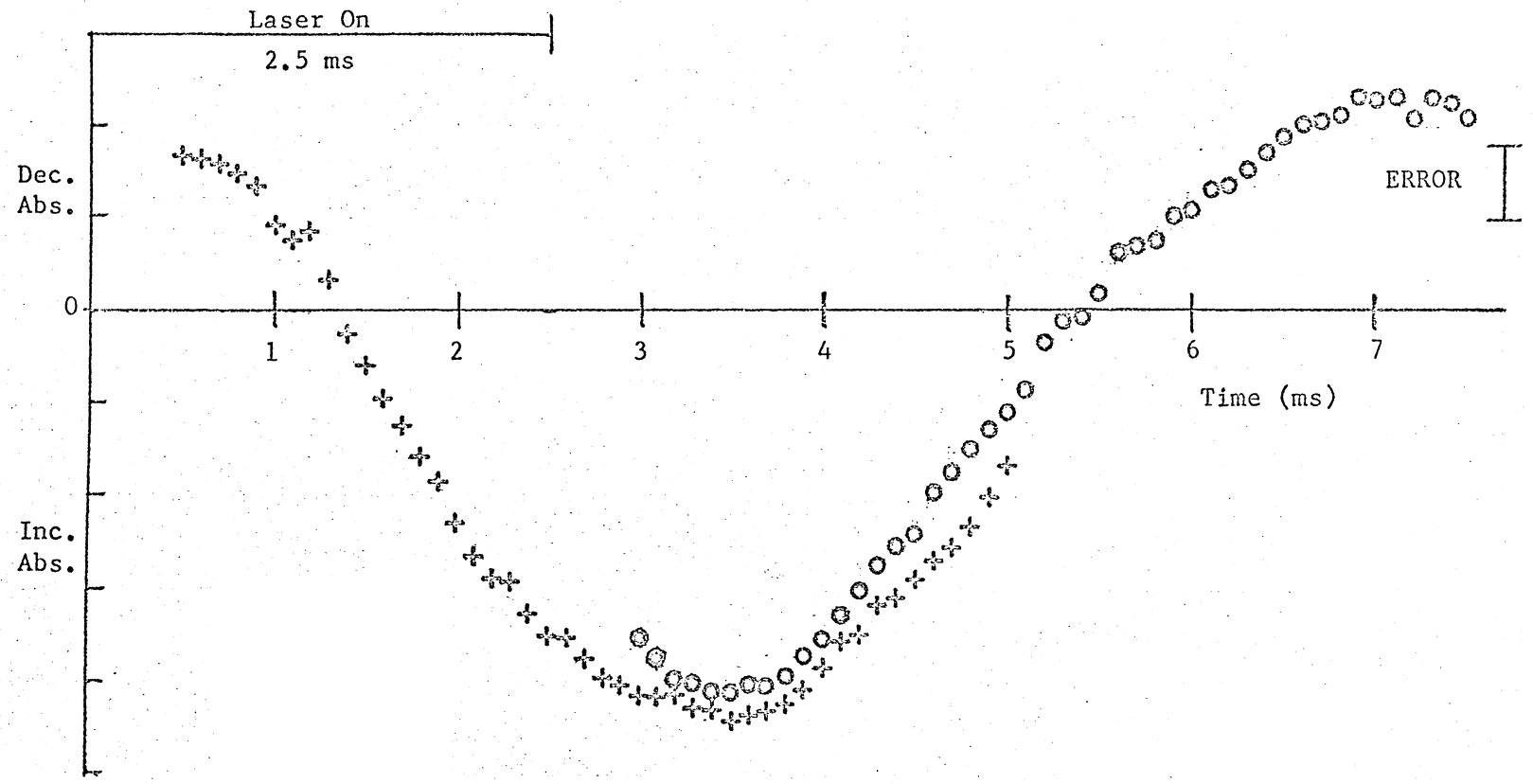


Figure 5. SIGNAL AT 4923 Å.

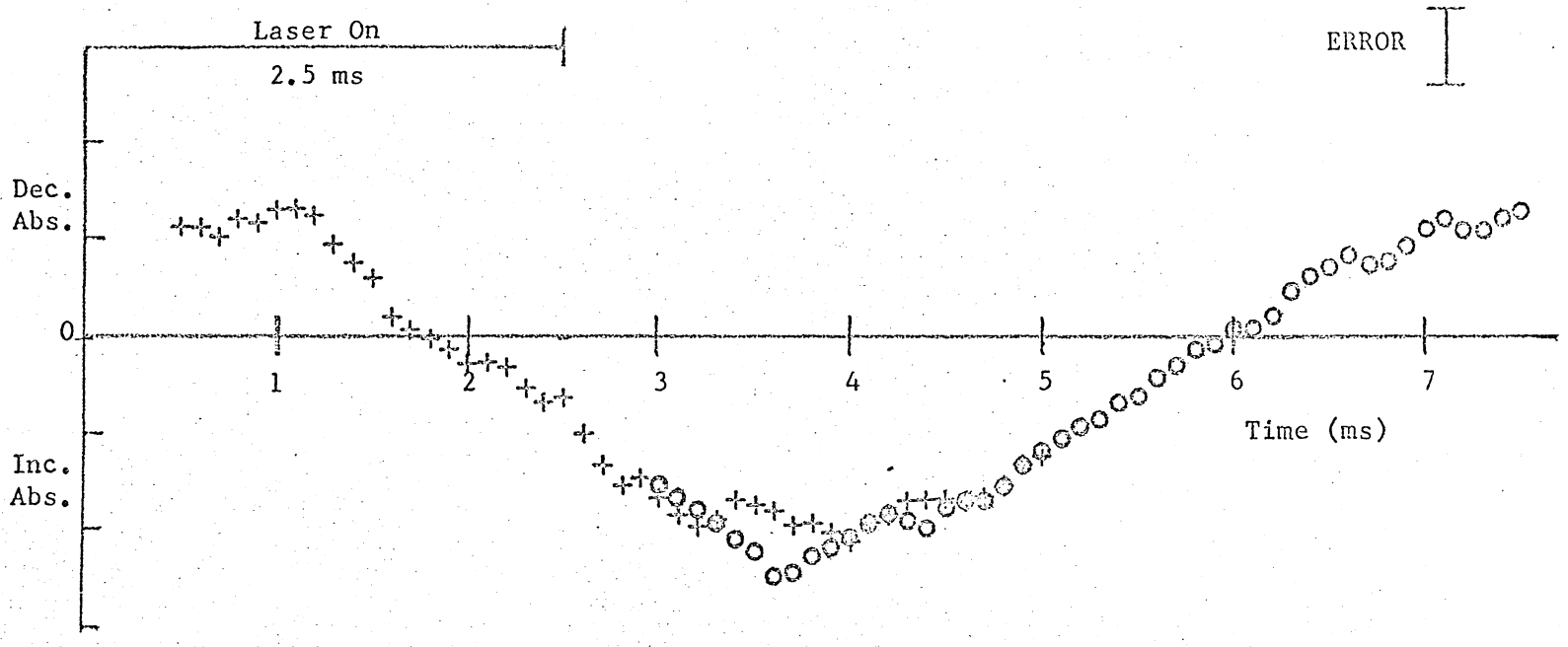


Figure 6. SIGNAL AT 4993 Å.

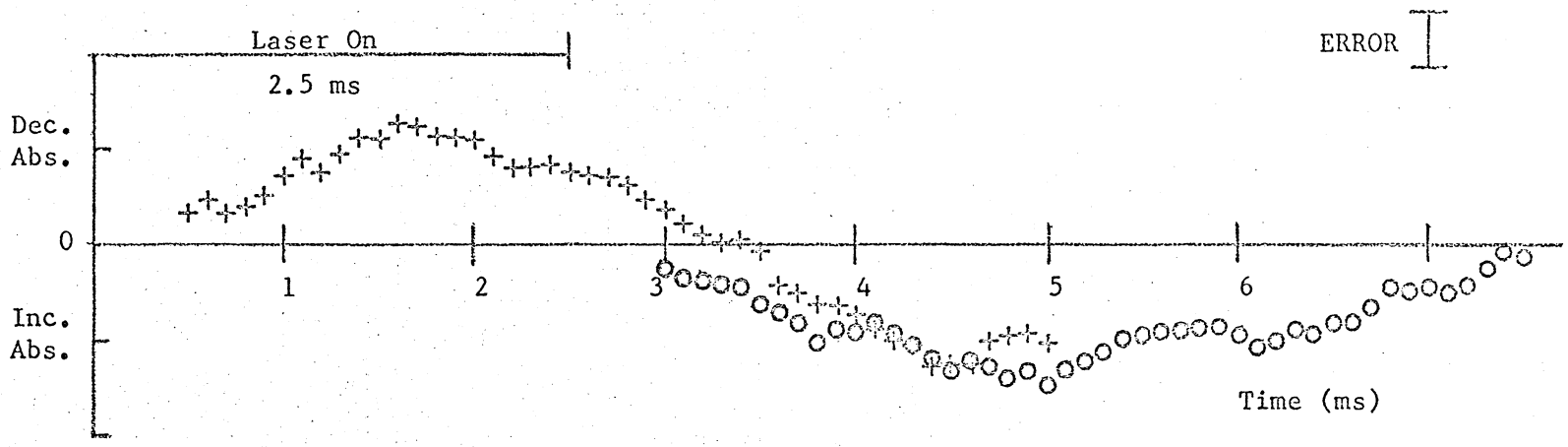


Figure 7. SIGNAL AT 5063 Å.

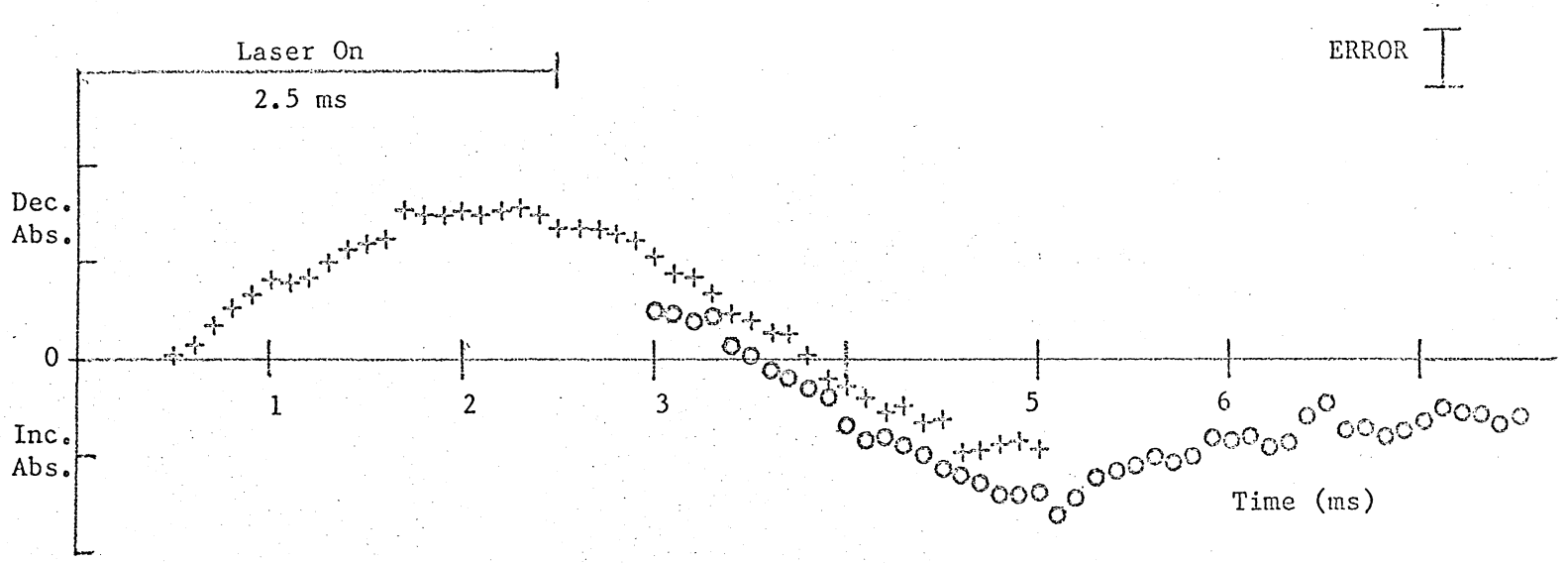


Figure 8. SIGNAL AT 5123 Å.

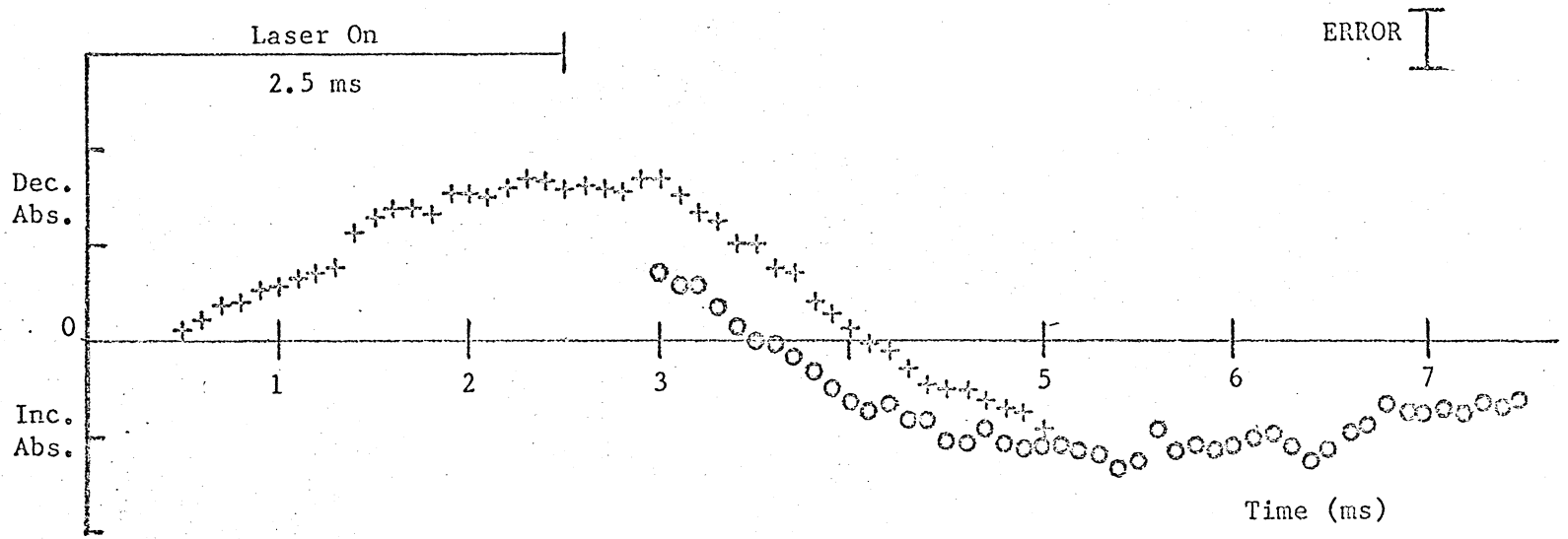


Figure 9. SIGNAL AT 5193 Å.

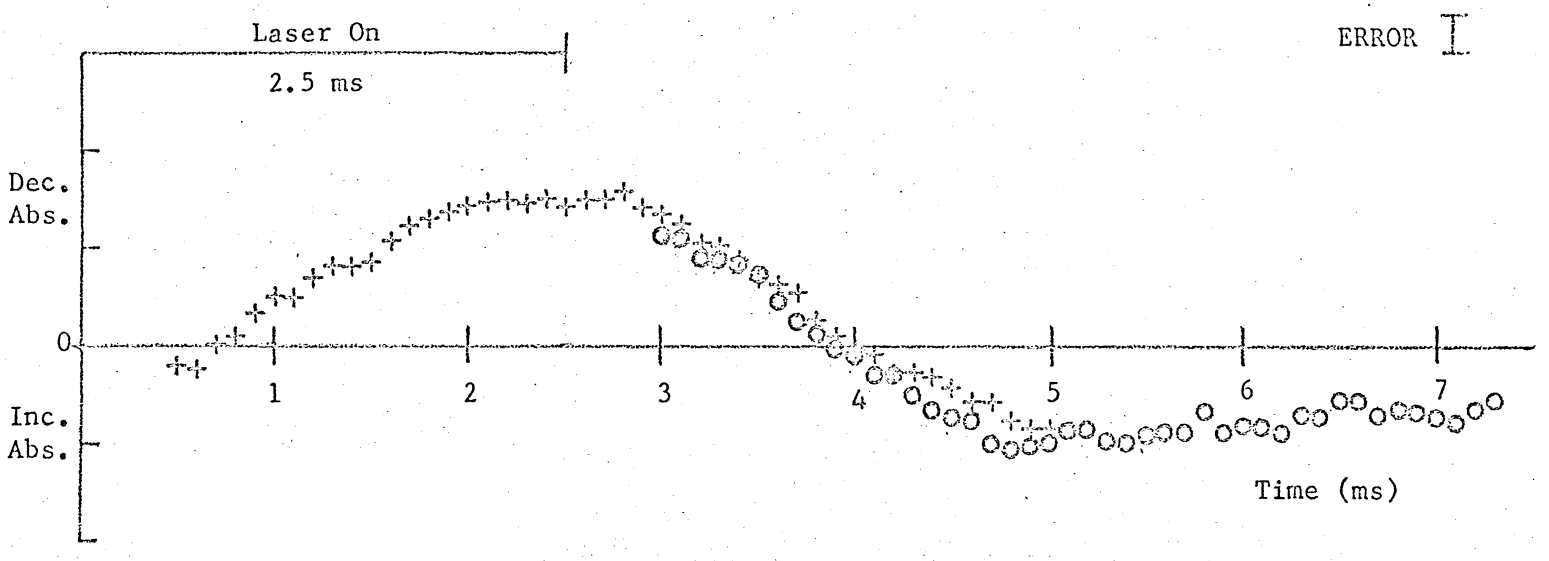


Figure 10. SIGNAL AT 5263 Å.

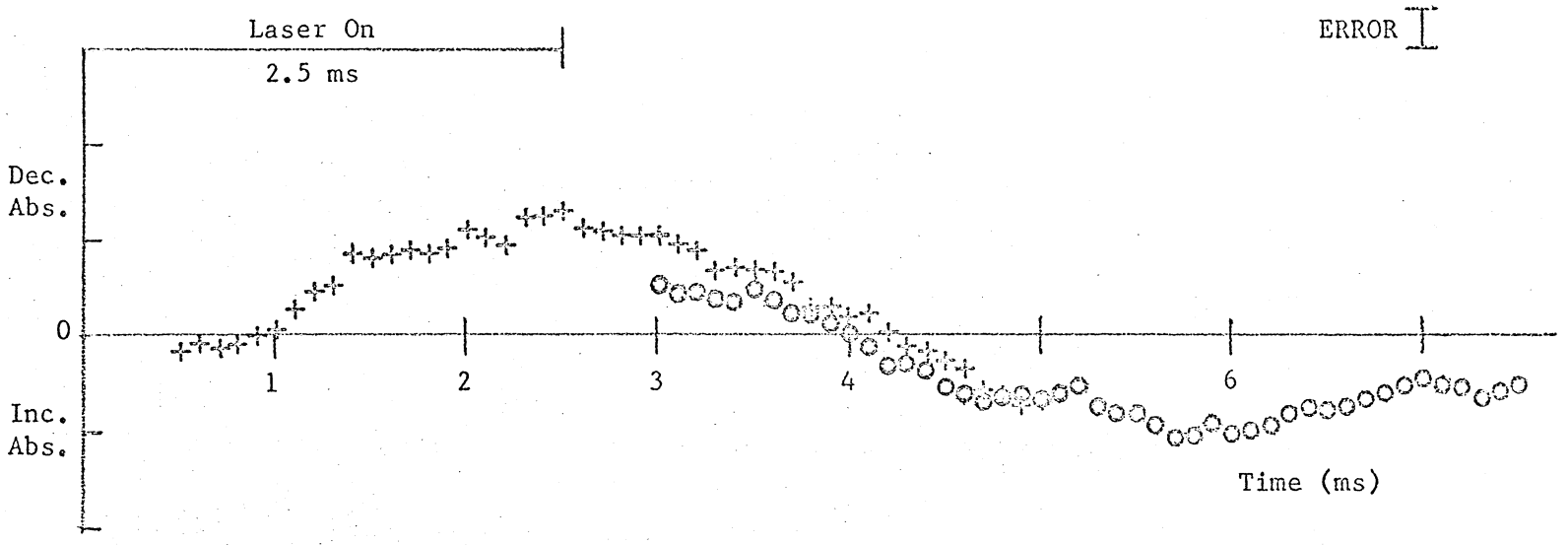
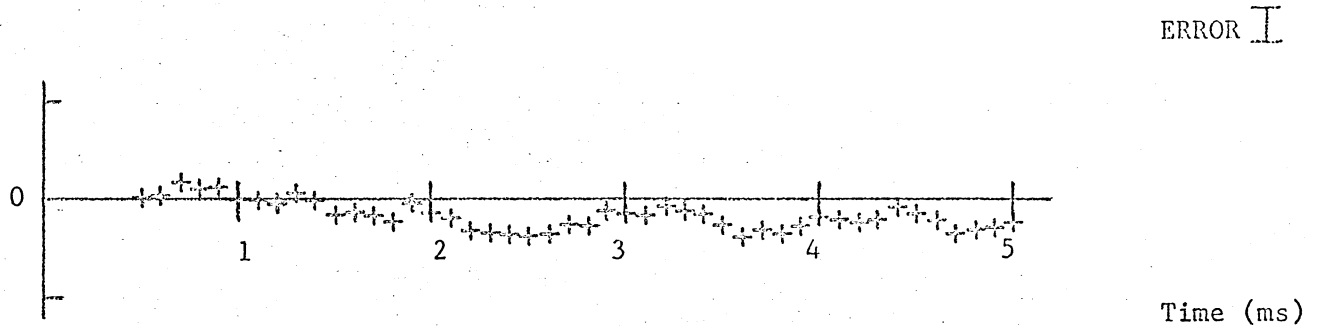


Figure 11. BACKGROUND AT 5263 Å.



negligible system drift. The zero line on each graph, $\Delta\alpha = 0$, represents the instrumental zero, but it does not necessarily represent zero excitation.

The data represent total signal behavior for a range of wavelengths with associated energies less than the gap energy. At first glance, the graphs fall into a pattern resembling sinusoidal behavior in time. An extremum in amplitude occurs at or soon after laser shut-off. A polarity reversal occurs near 4993 Å in the sense that, for shorter wavelengths, the extremum is that of increased absorption, while, at longer wavelengths, the other extremum prevails. This will be covered in more detail in the next section.

The quality of data is better than in previous work. Earlier, the apparatus was set up on two tables in a room with numerous windows; it was hard to control excess vibrations and outside light for both day and night runs. The present data were taken in a closed, ground-floor room in a temperature range of 88 to 90°F. With the equipment set on the floor, any effects due to vibrations were negligible. Everett used a gate of 0.9 ms to extract a 10 ms signal. With a 5 ms time base, a gate of 0.2 ms was used to gain better resolution. A slightly wider gate would have produced less apparent noise.

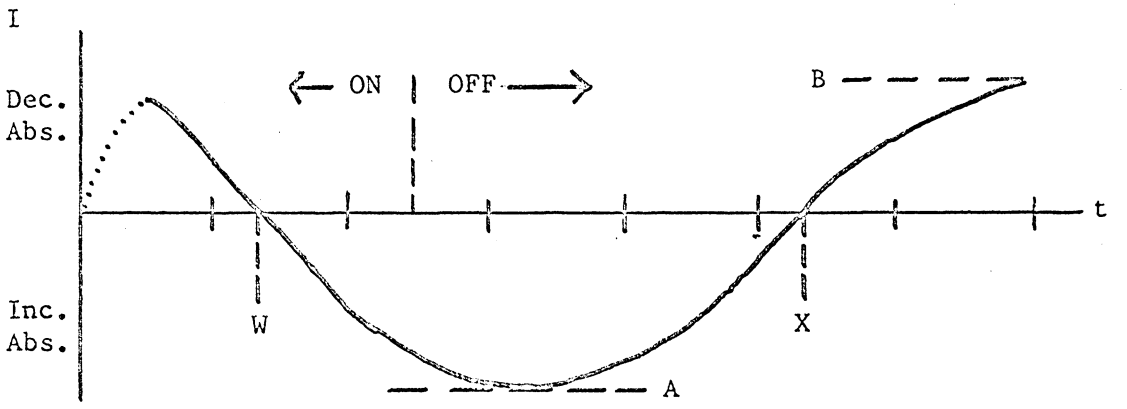
Two possible things affected the results, the stabilities of the primary light and chart recorder. The former was affected by its power supply which produced a nonperiodic drift of 3-4 %. The recorder print-out occasionally showed large high-frequency fluctuations; such data are not used for this paper. The cumulative RC, or characteristic response time of the PM tube circuitry, was found to be of the order of 2-3 gate widths. This makes the first 0.5 ms of recorded signal of little value for analysis in cases where the signal achieves a relatively large magnitude in that time.

VII. ANALYSIS AND CONCLUSIONS

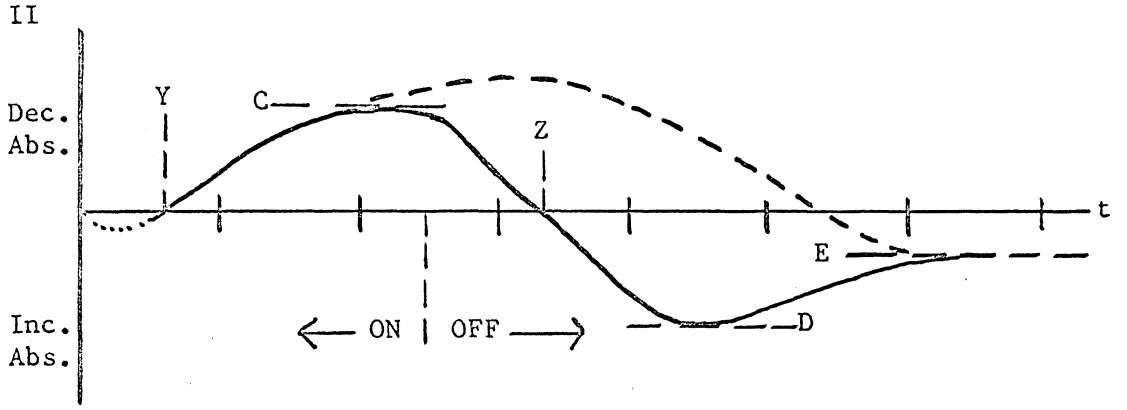
A good starting point in analyzing these data is to examine work already done with this crystal. Everett concluded previously that the signal reversed polarity in the region of 4900 to 5000 Å and reached its extreme value after laser shut-off, whether it is a positive or negative change in absorption. Using a relatively wide gate made necessary in that work by limitations on the system, such a conclusion appeared valid. From Everett's data, each wavelength displayed a signal of form Type I, Figure 12, though it may be reversed at wavelengths longer than 5000 Å as in Type II with the dashed line.

From these data, the signals at 4823, 4873, and 4923 Å are of form Type I. But the signals at 4993 Å and longer wavelengths are of Type II. This change, however, is gradual with wavelength. In trying to correlate corresponding features of the two forms, the beginning is the first extremum at or after laser shut-off. This is the instant in time from which decay will start with no more excitation; a plot of wavelength versus time of occurance of extremum will be helpful, as in Figure 13. Also of interest are the times when no change in transmission occurs; these suggest a discontinuity at 4993 Å, as in Figure 14. At first, an attempt was made to relate W and X to Y and Z (Figure 12) respectively as corresponding times. But W and Z bear an apparently closer relation to each other. This implies for consistency that A and D are related (Figure 13 is also consistent with this relation). Several characteristics of the

Figure 12. POSSIBLE GRAPHIC FORMS.

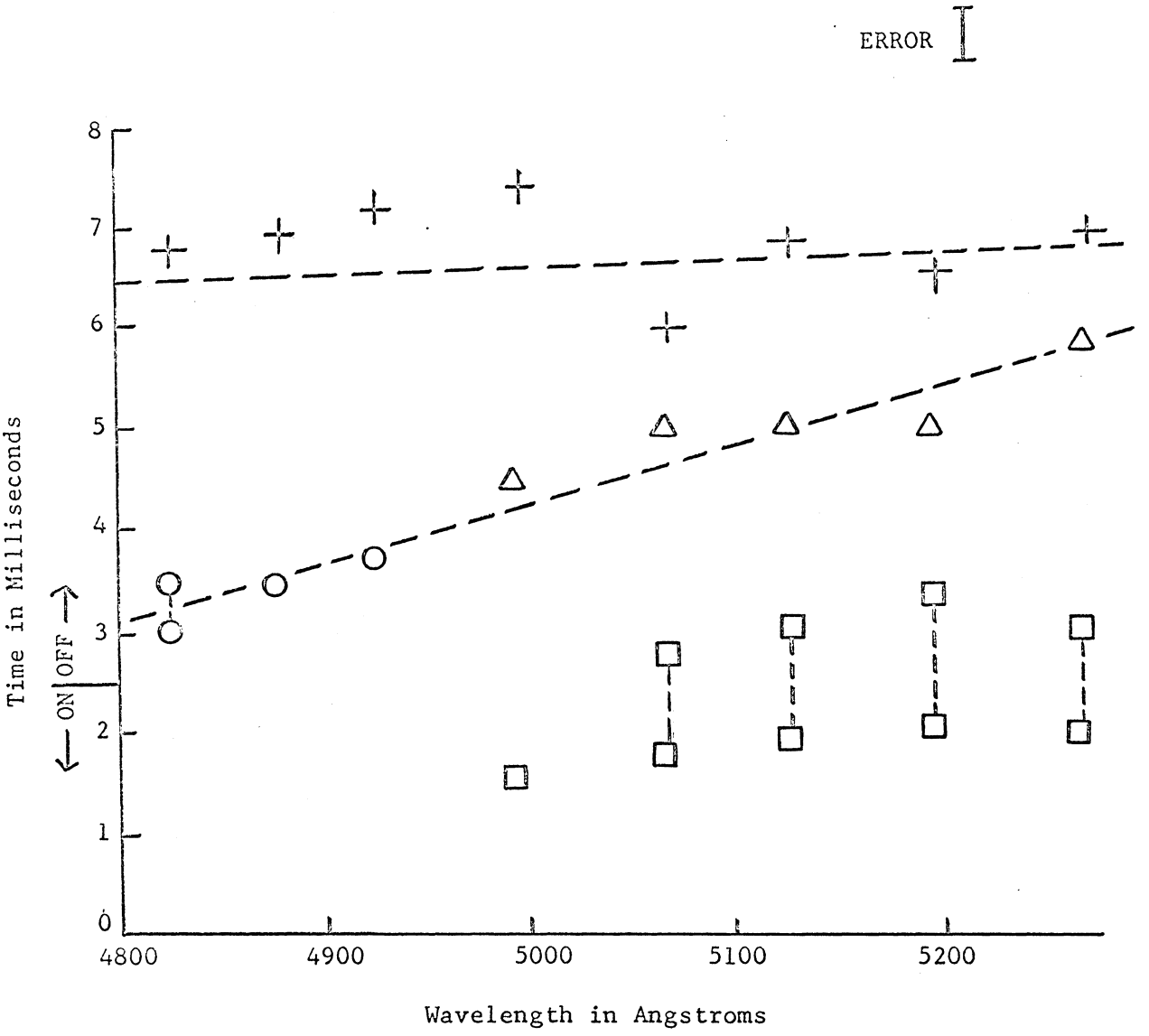


A = Extreme value after laser shut-off
B = Apparent steady-state value
W = Time when $\Delta\alpha$ = 0 before extreme value
X = Time when $\Delta\alpha$ = 0 after extreme value



C = First relative maximum near or after laser shut-off
D = Second relative maximum of signal
E = Apparent steady-state value
Y = Time when $\Delta\alpha$ = 0 before first relative maximum
Z = Time when $\Delta\alpha$ = 0 before second relative maximum

Figure 13. TIMES OF OCCURANCE FOR MAJOR FEATURES.



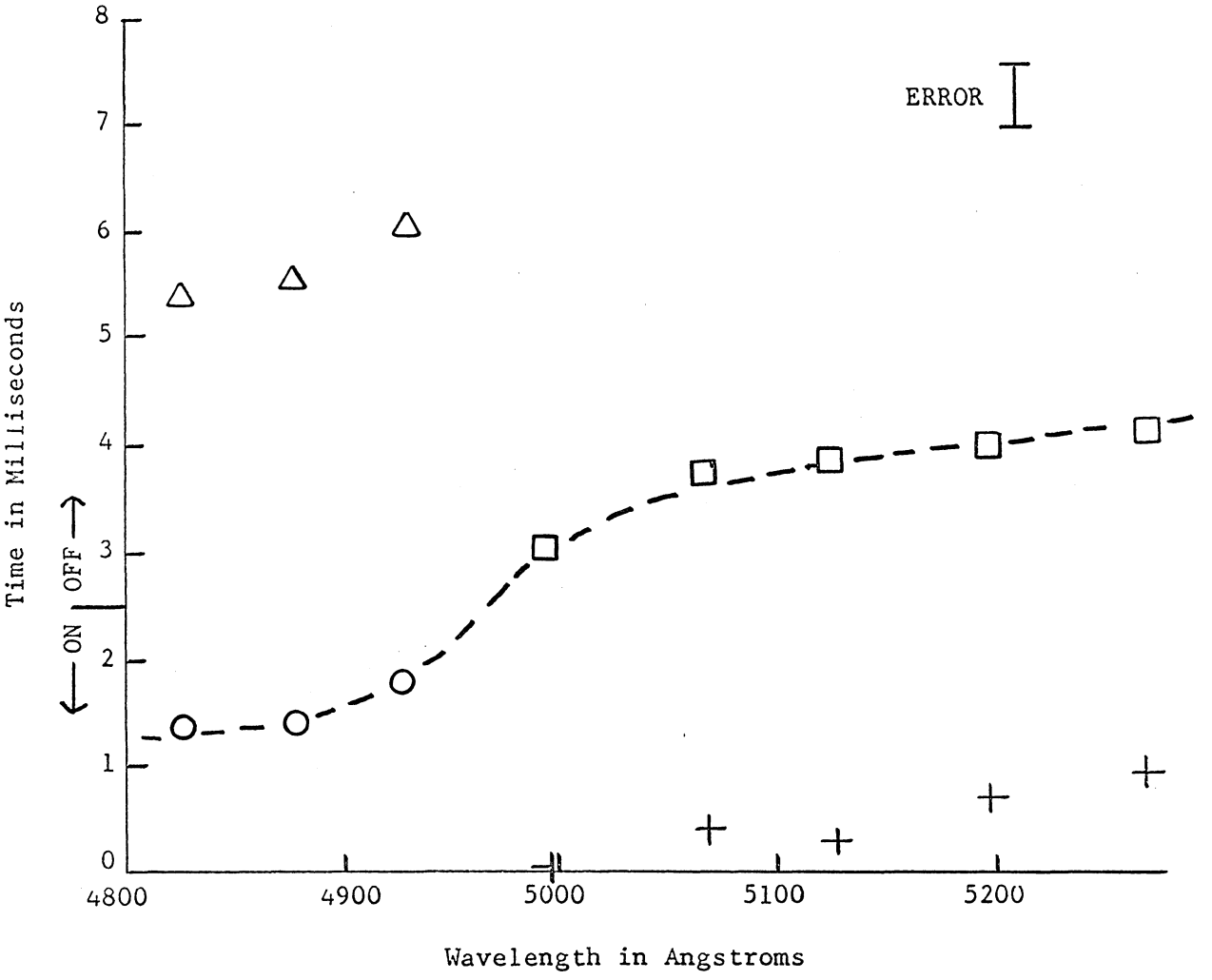
○ = Feature A, Figure 12

+ = Features B, E, Figure 12

□ = Feature C, Figure 12

△ = Feature D, Figure 12

Figure 14. TIMES WHEN SIGNAL COINCIDES WITH NO CHANGE IN TRANSMISSION



○ = Time W, Figure 12

△ = Time X, Figure 12

+ = Time Y, Figure 12

□ = Time Z, Figure 12

general signal behavior at all wavelengths investigated can now be summarized. There is a polarity reversal in the signals near 4993 Å in the following sense: The signals 4823, 4873, and 4923 Å have a negative polarity - Type I, Figure 12 - the sign of $\Delta\alpha$ from which each signal apparently begins and ends. The signals at 4993 Å and longer wavelengths show a positive polarity.

The following may correlate the concept of polarity reversal with the appearance of feature D, Figure 12, in the signals at 4993 to 5263 Å. The experimental parameters of significance are the gate width and laser heating of the sample. Feature D may not have been observed in Everett's data due to his wider gate of 0.9 ms. The 0.2 ms gate used here produced much better signal resolution. More data should be taken at longer wavelengths to see if a transition wavelength exists, and, if so, what it is.

Major and the author have observed an increase of 2-5 % in the DC voltage after the laser photons strike the sample. This implies that more light is being transmitted through the crystal. The instrumentation used here is not capable of displaying this component separately. Figure 15 shows what this may be. However, the proper treatment is unclear at this time; more research is being done in this area.

To find a suitable model to explain the author's data, he first turned to Stringfellow and Bube.[7] They have done a very extensive study on the photoelectric properties of ZnSe. Figure 16 displays a general correlation between their study and previous work by Major. Thus it is possible that this crystal has properties similar to theirs. They found copper to be a major factor in the photoelectric properties of II-VI semiconductors where it substitutes for zinc as an acceptor. Their primary ZnSe crystal had

Figure 15. POSSIBLE EFFECT OF LASER HEATING IN SAMPLE.

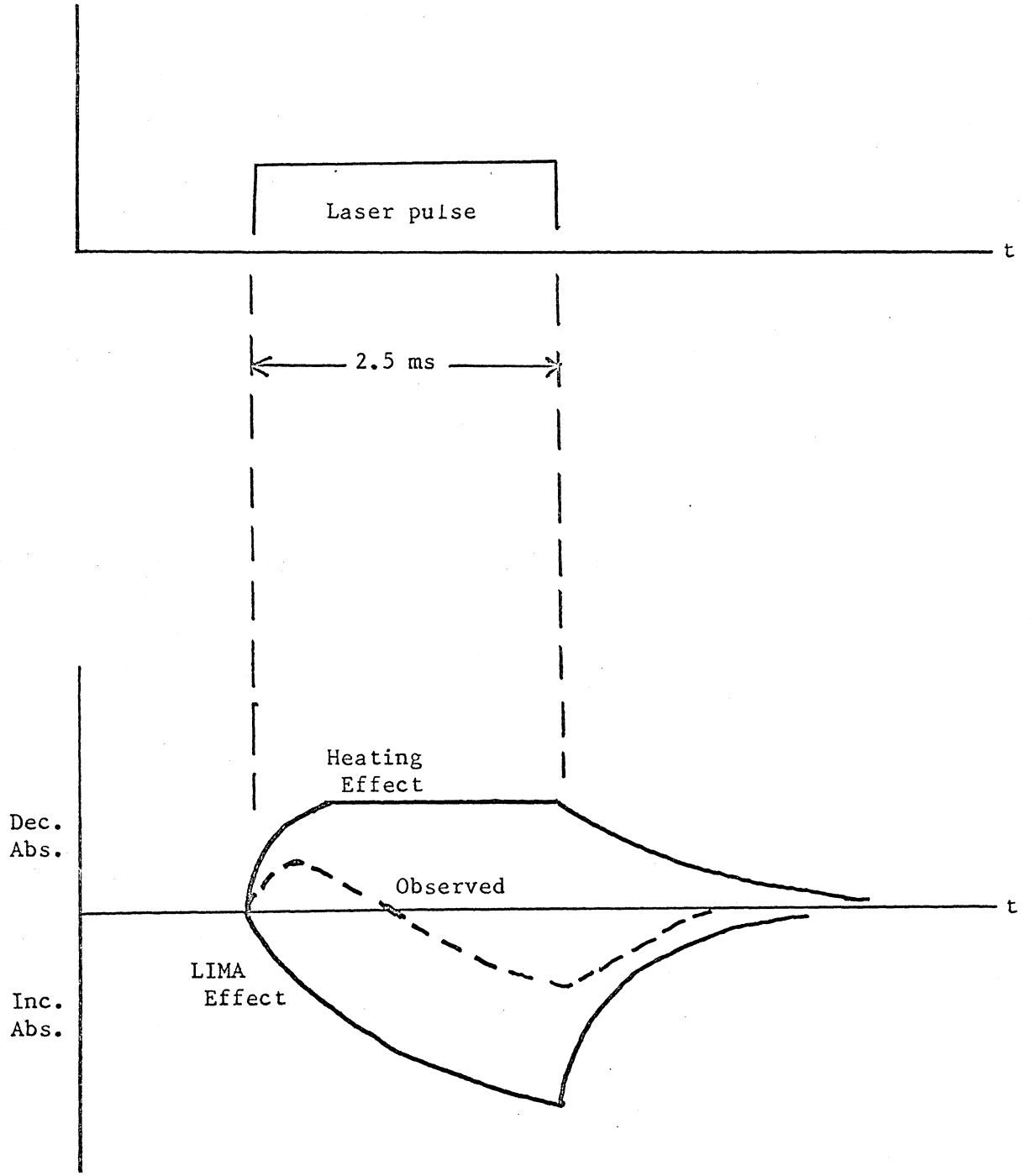
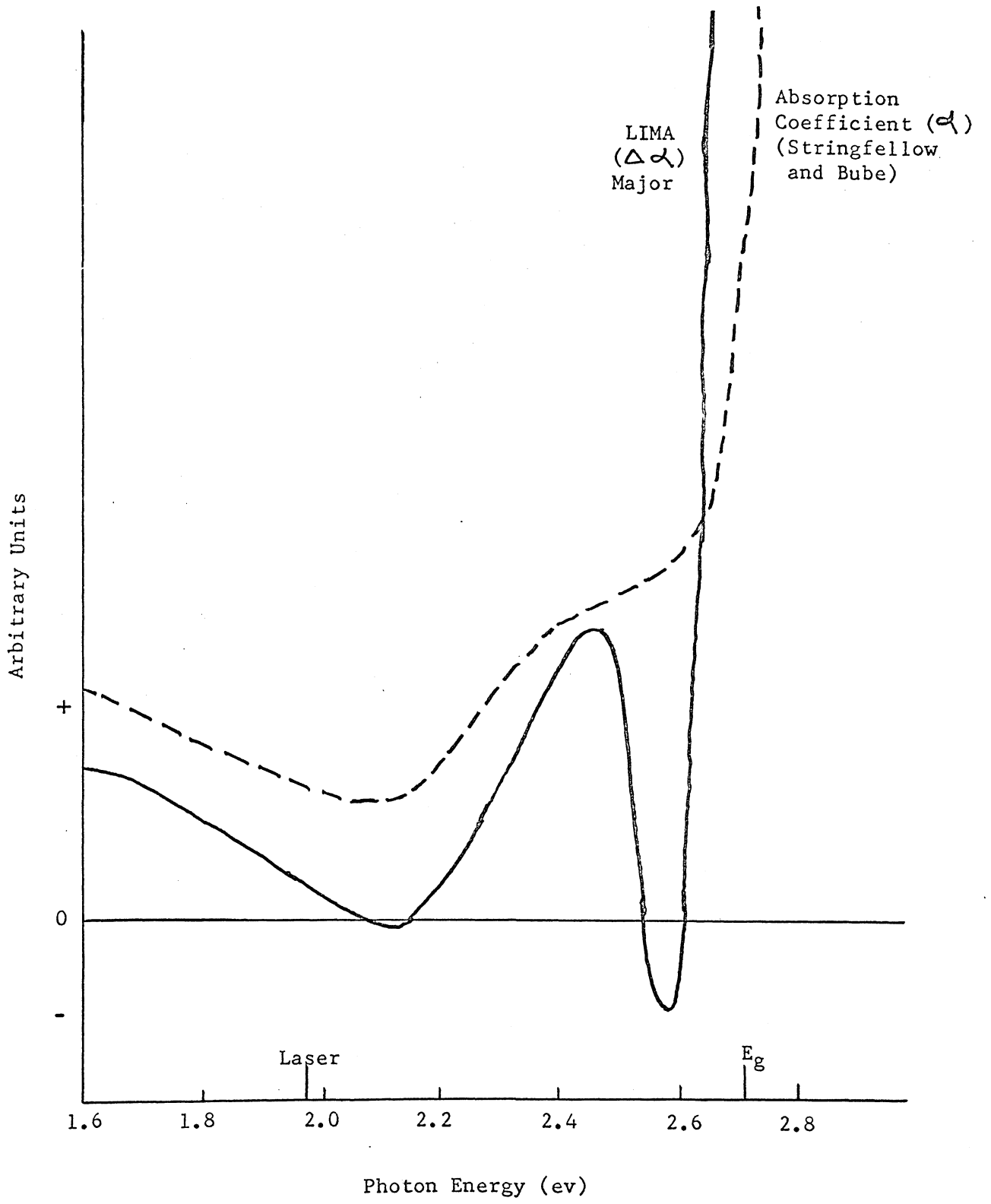


Figure 16. COMPARISON SKETCHES OF THE ABSORPTION COEFFICIENT AND LIMA FOR A SPECTRA OF PHOTON ENERGIES (Everett)[8].

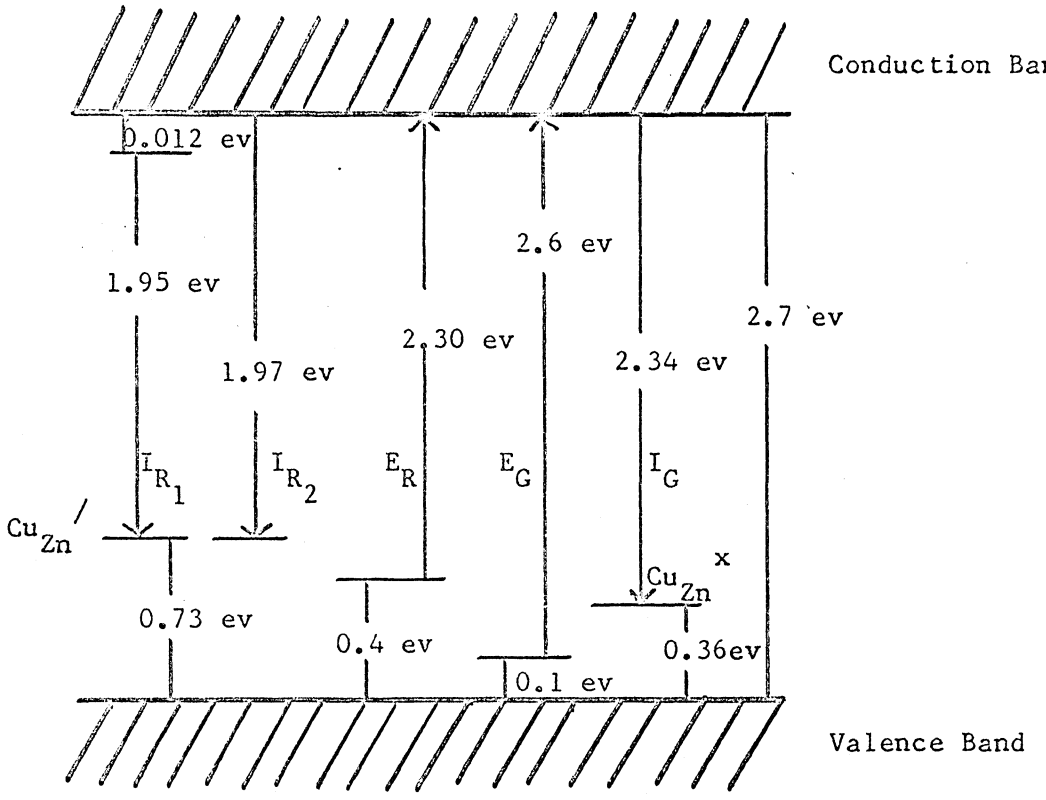


two copper ions present, Cu^{+}, known as $Cu_{Zn}/$, which was responsible for red luminescence and Cu^{++}, or Cu_{Zn}^{x}, responsible for green luminescence. The former dominates the latter having a capture cross section, for electrons, larger by a factor of 10^{3}. Figure 17 displays their proposed multivalent copper model which consistently describes their findings.

Most of the ZnSe:Cu crystals used by Stringfellow and Bube had a copper concentration of 30 ppm. The crystal used here was analyzed with an electron microprobe[9] and was found to have 4.0 % iron and 0.15-0.20 % nickel. Copper was not detected, but it may be present in amounts up to 500 ppm. There may be more than enough copper in this crystal to produce effects similar to theirs, but a better crystal analysis is needed to be sure.

A recent model proposed by Conway[10] for CdS has several energy levels within the band gap to explain why the change in the absorption coefficient continues to increase after laser shut-off. Even though it is a phenomenological model with no specific impurities identified and each signal is of one polarity only, the model may still be good for much of what is occurring inside this ZnSe crystal. Figure 18 displays the model which is based upon holes being redistributed over the trap levels after laser shut-off. The holes are first trapped at type 0 levels (N_i designates type i trap concentrations and ρ_i trapped hole concentrations). The holes are transferred at "rate γ_1 to type 1 levels and (then) to both type 2 and 3 levels with rates γ_2 and γ_3. Holes disappear from type 2 and 3 levels by recombination with free electrons at rates β_2 and β_3, respectively. Most of the excited electrons are trapped."[10] Conway assumed thermal effects to be negligible. He obtained good fits of his data to this model

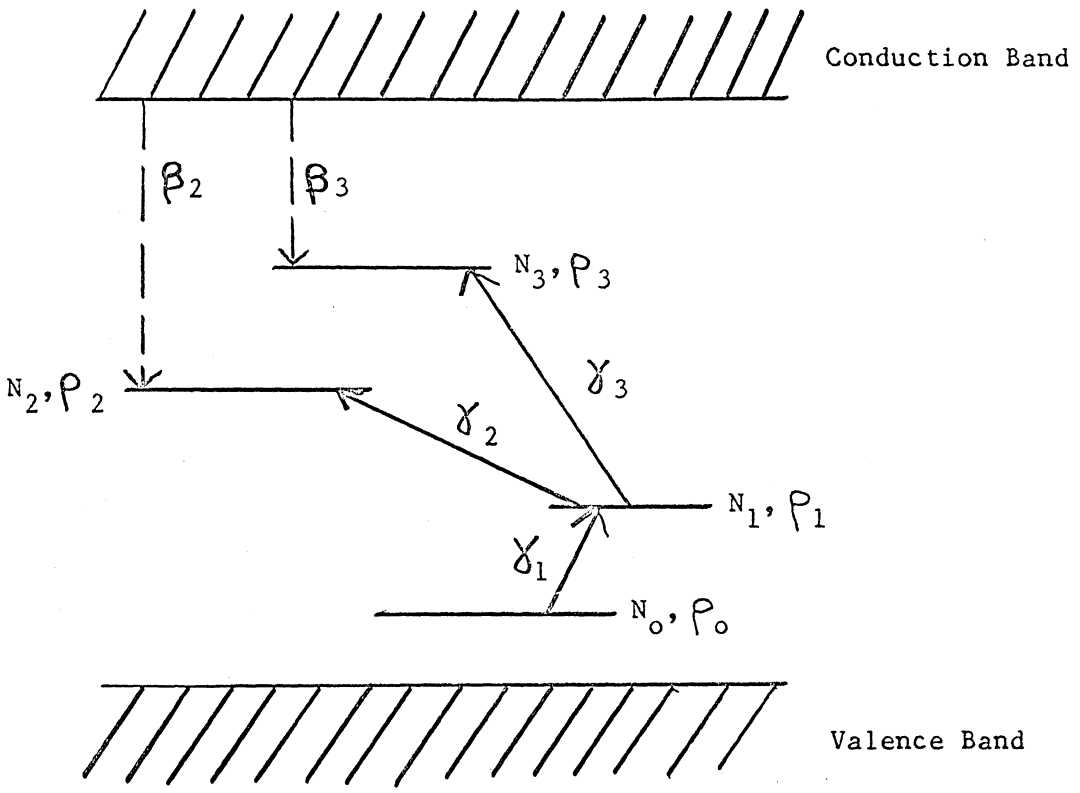
Figure 17. MULTI-VALENT COPPER MODEL: ZnSe:Cu (Stringfellow and Bube)



$Cu_{Zn}/ \rightleftharpoons Cu^{+} \Rightarrow$ Red

$Cu_{Zn}^{x} \rightleftharpoons Cu^{++} \Rightarrow$ Green

Figure 18. PROPOSED MODEL FOR CONTINUED LIMA BUILDUP (Conway).



using a computer and trial parameters for the β's and γ's. This model is a good beginning, but other components must be added due to its handling only one polarity at a time.

Further studies of this crystal should include data taken at longer wavelengths and with slower chopping frequencies. The frequency of 114 Hz limits signal duration to 8.8 ms. The signal appears to reach a steady state in 4.0 to 4.5 ms after laser shut-off, but this may continue for as long as 10-15 ms. Data should be taken in the infrared to see how ZnSe compares with CdS at longer wavelengths and at lower temperatures to examine the suggested role of laser-induced heating in the sample.

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X. APPENDIX

Monochromatic light of known wavelengths in the range of experimental interest were put through the detection system for calibration. Below is the data which implies an error of 23 $\pm$ 3 Å which must be added to each wavelength read from the detection system monochrometer.

Element	Dial(Å)	True(Å)[11]
Helium	4992	5016
Helium	5855	5876
Hydrogen	4838	4861
Krypton	5850	5871
Mercury	5440	5461
Mercury	5770	5791

TABLE I

DATE	WAVELENGTH (In Angstroms) DIAL	TRUE (±3 Å)	IDENTIFYING NUMBER R:Rise D:Decay	NARROW SLIT (0.20 mm)	WIDE SLIT (0.25 mm)
1/18-19/72	4900	4923	2R,1R	X	
1/19/72	4900	4923	6R,2D	X	
1/21-22/72	4900	4923	4R,5R,1D	X	
1/23/72	4970	4993	1R	X	
1/24/72	4970	4993	2D	X	
1/26/72	4850	4873	1R,2R	X	
1/27/72	4850	4873	1D,2D	X	
1/28/72	5040	5063	2R,3D,2D	X	
1/31/72	5040	5063	1R,1D	X	
2/ 1/72	5100	5123	3R,3D,4D	X	
2/ 2/72	5170	5193	5R,5D,6D	X	
2/ 3/72	5170	5193	1R,1D		X
2/ 4/72	5170	5193	2R		X
2/ 5/72	5170	5193	3R,3D,4D,4R		X
2/ 7/72	5100	5123	2R,1R,2D,1D		X
2/ 8/72	5040	5063	3R		X
2/ 9-10//2	5040	5063	4R,5R,4D		X
2/11/72	4970	4993	2R,4D		X
2/12/72	4900	4923	3R,3D		X
2/16/72	4850	4873	3R,3D		X
2/17/72	4800	4823	1R,1D		X
2/20/72	5240	5263	1R,2R,1D		X
2/22/72	5240	5263	Background		X

XI. VITA

The author was born on July 6, 1946 in Lynchburg, Virginia. He was raised there and educated in the Lynchburg Public Schools. He was graduated with honors from E. C. Glass High School in June 1964, where he was active in the high school band and Science Club.

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After working for several months as a computer operator, he entered the University of Richmond to continue his education. He plans to work in the field of solid state physics using scientific programming as a tool.