# Transient photoconductivity measurements in semi-insulating GaAs. II. A digital approach

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We describe an experimental setup designed to study photoconductive transients in semi-insulating materials. The method, known as photoinduced transient spectroscopy, is based on a digital signal-averaging technique. Although this digital method eliminates or reduces many of the experimental problems encountered when using an analog approach, several new problems arise. The method is described, and the difficulties are illustrated using data obtained from both Cr-doped and nominally undoped samples of GaAs.

## I. INTRODUCTION

Several experimental techniques have been developed to explore flaws in semiconductor materials that introduce deep energy levels for the carriers. Many of these techniques lose their sensitivity when the resistivity of the material increases. One technique that appears suitable for high-resistivity materials is often referred to as PITS (photoinduced transient spectroscopy). Several difficulties with the method do exist, however, and precautions must be taken if the data is to be interpreted intelligently.

The preceding paper[1] described a PITS experimental arrangement whereby data were collected in an analog fashion. Some of the problems of the technique were discussed. This paper describes an improved experimental arrangement, where the data are averaged, digitized, and stored in a computer for later analysis. This digital approach solves some of the problems raised in the preceding paper. Using the computer allows much more complete analysis of the data. This analysis, however, reveals that some of the assumptions underlying the analysis are not satisfied in the semi-insulating GaAs samples that we studied.

## II. EXPERIMENTAL CONSIDERATIONS

We have made PITS measurements on several semi-insulating materials. In addition to Cr-doped and nominally undoped GaAs, which provide the results reported on here, we have also studied both doped and undoped CdTe and CdMnTe. Results for these latter materials have been reported elsewhere.[2] Our samples are usually square or rectangular in shape, with the major dimension about 5 mm, and of thickness from 500 to 800 $\mu$m. Samples of arbitrary shape may be used, however. The samples are mounted to the heat sink of the cryostat with vacuum grease.

A schematic of the experimental apparatus is shown in Fig. 1. The system, for ease of description, can be divided into three sections: the temperature control system, the optical system, and the electronics and data recording system. Both the temperature control system and the electronics/

data recording system have been significantly modified from the arrangement discussed in the preceding paper. We will discuss each system in detail.

The sample is placed in a small Joule–Thomson refrigerator. The temperature can be set either manually or by computer. By means of a silicon diode temperature sensor and a small heating resistor, the temperature can be maintained at any temperature between 78 and 375 K. The temperature can be set with a precision of 0.1° and easily maintained within 0.1° of the setpoint for periods as long as several minutes. The system is manufactured by MMR Technologies, Inc.,[3] and has been modified to accept computer control.

Our optical system consists of a tungsten source which passes through a electromechanical shutter and a silicon filter and is then focused on the sample. The tungsten lamp is, of course, a broadband source. The use of such a source requires us to use a mechanical shutter or chopper. Electro-optic shutters provide adequate extinction for only one specified wavelength and would thus not be suitable here. We have used both choppers and a mechanical shutter, the latter providing better results as discussed below. Our shutter uses a spring-loaded closing mechanism, and has a turn-off time of less than one millisecond when operating with an "open" time of 1 ms.[4] Normally, we run the shutter at a frequency of about 4 Hz with an "open" time of 100 ms. When operated in such a fashion, the turn-off time is considerably slower. We will discuss below the problem that this relatively slow extinction of the light poses. Before reaching the sample, the light passes through a filter consisting of a polished slab of silicon. This restricts the light actually reaching the sample to energies less than 1.1 eV.

Electronically, our system is very simple. A constant voltage is applied across the sample, and the current is measured by monitoring the voltage across a resistor in series with the sample. This signal is fed through a variable gain, high impedance operational amplifier before entering the analog-to-digital converter (ADC). The impedance of this preamp is greater than $10^{12}$ $\Omega$. The signal is then digitized using an ADC capable of making 18 000 conversions per second. Usually, however, the converter is run considerably slower. The digitized data is then stored on disk by the Apple IIe microcomputer.
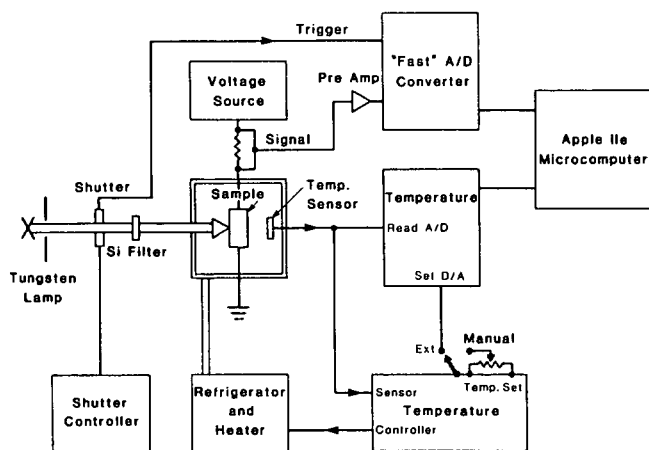
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FIG. 1. Block diagram of the apparatus used for the digital PITS experiments. The sample is illuminated by light from a tungsten lamp which passes through a silicon filter. The electrical system consists of a voltage source and a resistor in series with the sample. Cooling is provided by a Joule–Thomson refrigerator, with temperature stability maintained by a temperature sensor and heater combination. The heart of the apparatus is the Apple IIe microcomputer, which is triggered by the optical system, receives input from the electrical system, and monitors and is capable of controlling the temperature system.

Rather than monitor the difference in photocurrent at two times during the transient decay while the temperature is swept, as per the analog approach, we hold the temperature fixed at some point, signal average until the signal-to-noise ratio is adequate (usually 32 pulses is sufficient), and then record the entire transient. The data can be sampled at 1024, 512, or 256 points (equally spaced in time) with 12-bit accuracy. The temperature is then raised to the next setpoint. By recording the entire transient, we can get all the information available in one series of fixed temperature points. Temperature steps of 2° usually provide adequate temperature resolution. The stored data can then be analyzed using several different rate windows. Our choice of rate windows is limited at the fast end by the time required to extinguish the light and at the slow end by the decay of the photocurrent itself.

## III. ADVANTAGES OF THE DIGITAL APPROACH

The experimental arrangement described above is based on a digital recording of the data. This method of data acquisition allows not only much better control of the data analysis, but also reduces some of the problems encountered in an analog approach to PITS experimentation.[1] In this section we will briefly discuss the advantages of the digital approach.

In the preceding paper describing the analog method, one of the major problems encountered was determining the proper rate at which to sweep the temperature. If the temperature is raised too rapidly, the position of the maximum in the PITS signal will be skewed toward higher temperatures. In a PITS measurement, each exciting pulse is assumed to create a trap occupancy that is independent of the thermal history of the sample. This assumption is not valid for rapid warming rates.

The digital approach utilizes a different method for thermal activation of the occupied traps. Rather than sweep the temperature (either slowly or rapidly), the temperature is held fixed at some point while the data is recorded. Then the temperature is raised to the next fixed point, and only after the temperature is stable at this new point is the process repeated. With adequate care, the temperature varies by at most 0.1° while the data is being recorded. Thus the temperature skewing effect noticed in the analog technique is not just reduced, but entirely eliminated.

A second major advantage of the digital approach is that all the data is collected in one series of fixed temperature measurements ranging from low to high temperature. Thus the sample needs to be cooled only once. It is notoriously difficult to make reasonably ohmic contacts to high-resistivity materials such as semi-insulating GaAs. The effect of repeated thermal cycling on these contacts is usually deleterious. In the analog approach, it is necessary to cool and heat the sample separately for each set $t_1$ and $t_2$ of time constants. There is no guarantee that the contacts will even remain physically connected to the material during this cycling, and it is likely that the electrical properties of the contacts change significantly. Measurements of "dark" current can vary by as much as an order of magnitude at the same temperature after repeated thermal cycling. While there is no assurance that the properties of the contacts do not change during the single heating of the sample used by the digital approach, the magnitude of any changes should be greatly reduced.

An additional benefit of using a set of fixed temperature points rather than ramping the temperature is that while remaining at a given temperature, the PITS signal can be averaged for as long as is necessary to reduce the noise level. The software designed for the experimental arrangement reported here allowed the averaging of the transients from a number of light pulses equal to any power of two. As reported elsewhere,[5] for most cases, only 32 signals were averaged, although in extreme cases, considerably more were used. The amount of averaging is limited only by the ability of the refrigerator to maintain a stable temperature and the operator's patience. It should be noted that the majority of the noise on the signal was 60 Hz noise picked up from the stepper motor used to rotate the chopper. When the chopper was replaced by a mechanical shutter, much of the noise problem disappeared.

A final advantage to the digital approach is that the entire transient is recorded for each temperature point. With the complete decay available, it is a simple matter to analyze the data for any set of time constants $t_1$ and $t_2$. The technique does not allow the *range* of time constants to be extended (as will be discussed below), but the overall ease and speed of the analysis is greatly increased.

## IV. DATA ANALYSIS AND ITS PROBLEMS

Although the digital approach discussed above reduces or eliminates many of the technological problems inherent in PITS experiments, the problems of analysis of the data, and the veracity of the results obtained have not been addressed. The ability to scrutinize the digitized data thoroughly re-

veals in particularly striking fashion some of the pitfalls encountered in attempting to extract meaningful trap parameters from a PITS-type experiment. This section discusses the analysis of PITS data and the difficulties that can arise.

Once the data have been stored on disk, the goal is to derive from these data information concerning the deep levels that are present in the sample being studied. For each sample, we want to know what traps are present, and quantitatively what the activation energy, concentration, emission rate, and capture cross section are for each one. To extract this information from the data, they are analyzed in a manner identical to that of a DLTS experiment, which has been outlined in the preceding paper[1] and will not be repeated here. It should be pointed out that this analysis assumes that the emission rate of the traps in question is fast enough that detrapping occurs during the time when the current is being recorded, yet slow enough that the traps can be optically filled. The validity of this assumption has been thoroughly discussed elsewhere.[6]

The emission rate for electrons from a trapping level can be written in the form

$$e_n = AT^2 \exp(-E_n/kT), \qquad (1)$$

where $A$ is a material-related parameter involving electronic concentration, velocity, and emission cross section[1] and $E_n$ is the activation energy for the trap. Note that this emission rate has a simple exponential form. By recording the entire waveform it is an easy matter to check the exponentiality of the decay. As reported earlier,[5] we have found that the decay is *not* a simple exponential. Since the entire analysis outlined above is based on the assumption of exponential decay, the veracity of trap parameters extracted using the method is in doubt. The results calculated from the data may be not be quantitatively accurate.

We have attempted to find the form of the nonexponential decay. The obvious first choice would be the sum of two or more exponentials. The presence of two deep traps with nearly equal activation energies could lead to a signal comprised of two exponentials, one faster than the other. Such results have been seen in DLTS experiments, for example.[7] We have found, however, that much of our data requires not two, but three or four exponentials to be adequately explained.[5] Data showing the entire transient decay obtained from a Cr-doped sample of GaAs at 173 K is displayed in the topmost trace of Fig. 2. The top trace of Fig. 3 shows the log of this data. Although the log data appears relatively linear at long times after the light was extinguished, the upturn at short times reveals the presence of an additional rapidly decaying transient as well. When the slowly decaying exponential is subtracted from the data, the second trace in Fig. 2 remains. The log of this data (shown in Fig. 3) again displays an upturn at the short time end, suggesting the presence of yet another, even more rapid transient. This subtraction process can be continued until the number of remaining data points is insufficient for reliable determination.

Much of the data taken seems to require three or four separate exponential transient decays to be adequately analyzed. Relying on the sum of three or four exponentials to explain the data is problematic for two reasons. First, the
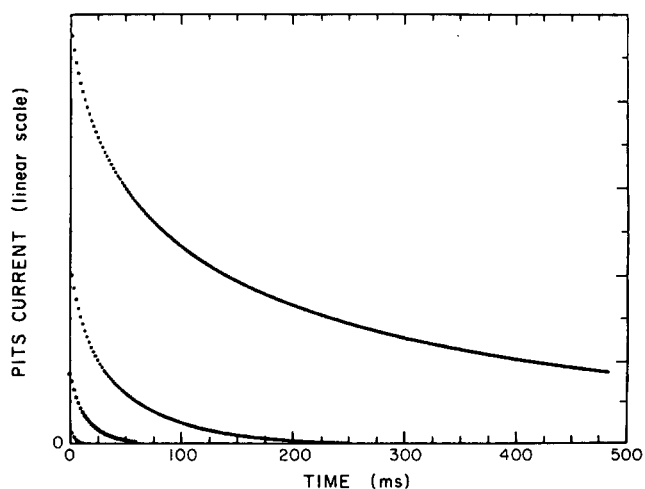


FIG. 2. Raw PITS signal as recorded for the Cr-doped sample D at 173 K. The top trace is the as-recorded photocurrent transient. The second trace is the remainder after the slowest exponential is subtracted off. The third trace is after the slowest two exponentials have been subtracted. The bottom trace is after the slowest three exponentials have been subtracted. The time constants for the four exponential components shown are 307, 61, 18, and 4.9 ms, as obtained from computer fitting.

larger the number of parameters used to fit a particular curve, the less reliable is that fit. By using eight parameters (amplitude and time constant for four exponentials) one should be able to fit almost any waveform. However, the eight parameters are not independent. The particular set of exponential parameters we choose to fit a particular curve is not necessarily unique. Local minima may exist in the standard error such that other parameter sets may give an equally good fit.

Perhaps even more disturbing is the underlying idea of explaining the data using as many as four exponentials. What does it mean to have decays that are the sum of four exponentials? The standard explanation for two-exponential decays is that two closely spaced traps are both active at roughly the same temperature. Our data, however, appears to be composed of the sum of three or four exponentials, and
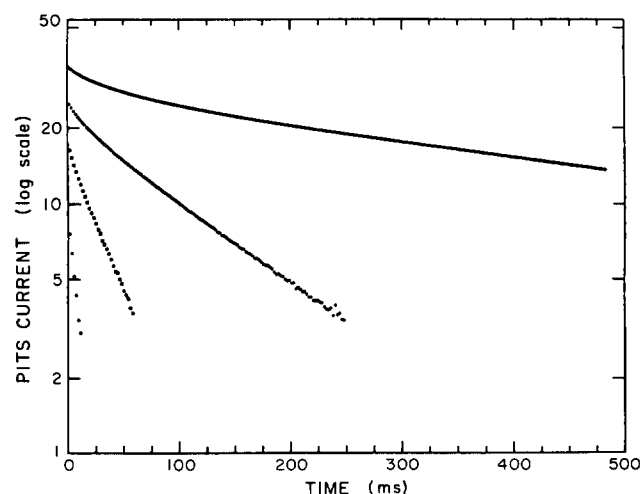


FIG. 3. Logs of the traces shown in Fig. 2. The top, second, third, and bottom traces are the logs of the corresponding traces in Fig. 2.

not at just one or two isolated temperatures, but at nearly all temperatures. The idea of three or four traps being electrically activated at all temperatures is simply untenable.

Leaving the problem of meaning aside for the moment, and continuing to view the data as the sum of exponentials, we have found that the method used to extract the parameters of the exponentials involved plays a large role in determining what particular set of exponentials will be extracted. For the work reported in both Refs. 5 and 7, the individual exponentials were extracted using a technique of successive subtraction. The slow part of the decay was fitted to an exponential. The contribution of this slow exponential was then subtracted from the data and the process repeated for successively faster exponentials. Danger is inherent in this process, in that the number of exponentials that will eventually be found to fit the data is determined at least in part by the length of the parts of the decay that are fit. By fitting the first exponential to the last 200 ms of a 500-ms transient, we get different results than when we fit only the last 50 ms. In addition, small errors in the slow exponentials are compounded greatly (exponentially!) in the faster ones. By creating "data" from the sum of known exponentials and attempting to analyze them, we have found that if the time constants of the exponentials are separated by about a factor of 2, we can pick them out fairly reproducibly. For time constants closer together than that, however, the parameters are increasingly suspect. The accuracy diminishes even further if the amplitudes of the exponentials differ substantially.

There are ways to overcome the successive subtraction problem. The data (still assumed to be the sum of exponentials) can be analyzed in such a way that the exponentials are solved simultaneously. One method for doing this is known as the method of moments.[8] In this technique, for a transient assumed to be made up of $M$ exponentials, the first $2M$ moments of the data are calculated. Using approximate starting parameters (amplitudes and time constants) for these exponentials, a Newton–Raphson iteration technique is used to adjust the parameters so that the moments calculated from them coincide with the data moments. Although the method of moments overcomes the successive subtraction problem, it is by no means a complete success. First, the number of exponentials to which the data is to be fit must be specified. Initial "guesses" for the exponential parameters must also be supplied. We have found, again, by creating "data," that if these initial choices are relatively inaccurate, the iteration procedure diverges rather than converges. As with the real data, if these initial guesses are not sufficiently close to the actual values, the error diverges or some of the parameters generated become negative. It is also somewhat disturbing that when the program is attempting to fit data composed of three known exponentials, the fit (as measured by the size of the error) is sometimes actually better when only one or two exponentials are fitted to the data rather than three! When the fit satisfactorily converges, the errors in the exponential parameters involved are usually quite small—typically a few parts per million in the amplitudes, and somewhat less than a percent in the time constants.

Even when solving for a number of exponentials simul-

taneously, rather than successively, it is still not assured that the solution will be unique. Different starting parameters could easily lead to a different set of exponentials. In addition, regardless of how the exponentials are determined, one further problem exists. The value chosen for the baseline of the exponential is crucial; that is, it is necessary to know the value of the dark current level at each particular temperature. We have found that small changes in baseline lead to rather dramatic changes in the values found for the exponential parameters, regardless of the method used to extract the exponentials. It should be pointed out that the baseline problem is not restricted to PITS measurements. Any experimental technique where the data is assumed to undergo exponential changes (such as DLTS, for example) is prone to this danger.

## V. RESULTS

In this section experimental results will be presented for representative Cr-doped and undoped semi-insulating GaAs samples. As was the case in the preceding paper, the emphasis here is not on the characteristics or identification of the detected deep levels, but rather on the measurement technique, and how the quality of the data is influenced by it. The results shown for the Cr-doped material can be compared to those obtained by an analog approach, and discussed in the preceding paper.

As noted above, the digital approach utilized here involves recording the entire transient decay after the light pulse is extinguished. With these data it is a simple matter to generate PITS "signals" analogous to those produced by the analog method. The closed circles in Fig. 4 show such results for a Cr-doped sample labeled D (different from the three discussed in the preceding paper) for $t_1 = 15$ ms and $t_2 = 45$ ms, thus giving a time constant of 12.2 ms. The temperature "scan" is characterized by three large peaks, with two smaller ones appearing as shoulders. As different time constants are chosen, and different temperature "scans" genera-
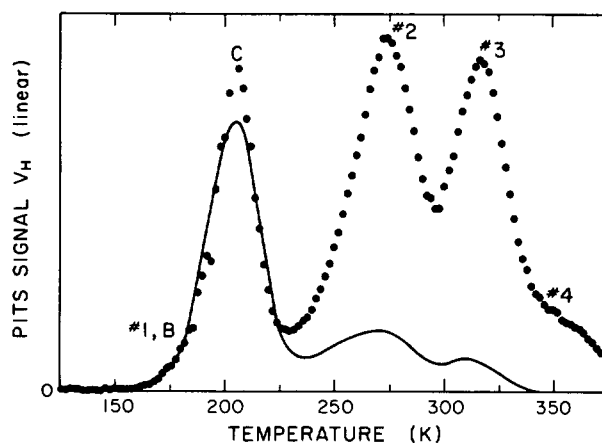


FIG. 4. Digital approach PITS signal, as plotted by computer, for Cr-doped sample D. Data, such as that shown in the top trace of Fig. 2, are analyzed for a time constant of 12.2 ms, with $t_2 = 3t_1$. When analyzed for other time constants, the small peaks labeled D1 and D5 were occasionally somewhat larger. The solid line shows a trace obtained for the same sample using the analog method.
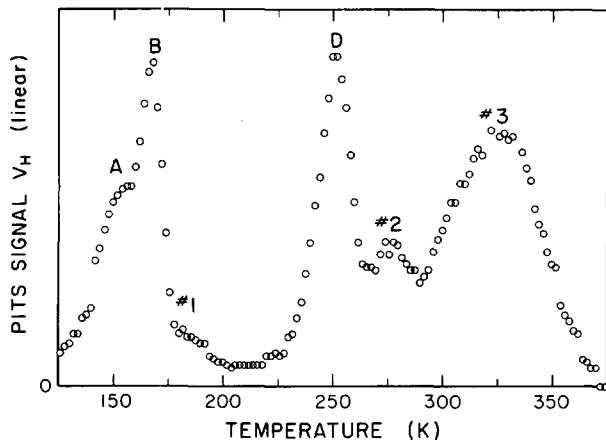
FIG. 5. Digital approach PITS signal for undoped sample E. The data were analyzed for a time constant of 12.2 ms, with $t_2 = 3t_1$.

ted, the position of these peaks shifts. These results are displayed in the form of an Arrhenius plot by the closed circles in Fig. 6 and will be discussed later. The solid line in Fig. 4 is a trace obtained using the analog approach on the same sample with the same time constant. The differences will also be discussed below.

Similarly generated PITS "signals" are shown in Fig. 5 for a representative undoped sample labeled E. The values for $t_1$ and $t_2$ (and thus the time constant) are identical to those for sample D. Again, some of the peaks are large, and thus easily detectable, while others appear only as shoulders on the side of the large peaks. When the temperature "scans" are generated for other time constants, the Arrhenius results are shown in Fig. 6 by the open circles. The straight lines defined by the points in the figure provide signatures for the various trapping levels present in the materials.

One distinct disadvantage of the present method (and PITS experiments in general) is the limited range of time constants that are readily available for use. The data shown in Fig. 6 involves a range of time constants of less than one order of magnitude. This should be compared to claims of up to seven orders of magnitude for experiments utilizing elec-
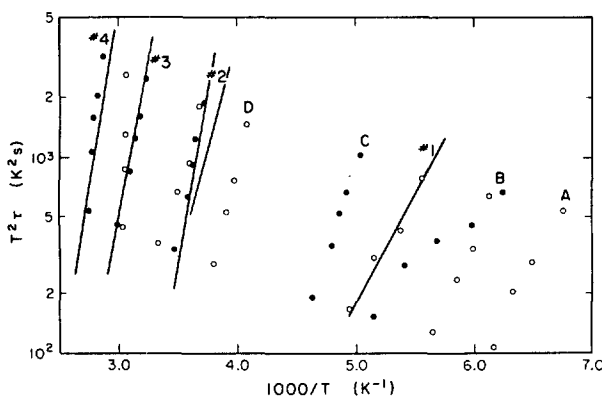


FIG. 6. Arrhenius plots for the data shown in Figs. 4 and 5. The emission signatures shown with closed circles correspond to the levels observed in sample D, and the open circles refer to sample E. The lines are taken from Fig. 8 of the preceding paper (Ref. 1).

trical pulses, rather than optical ones.[7] It would be an easy matter to add more points to the data shown in Fig. 6, but the added points would lie between the points already shown for each trap. It is much more difficult to add any further data that actually extend the measurements to longer or shorter rate windows.

The difficulty in extending the data to longer rate windows lies in the fact that the signal is a decaying one. The data shown already extends temporally out to 90 ms after the end of the optical pulse. By that time, the signal is practically equal to the dark current for most of the temperatures. For a few temperature points, there was still an appreciable amount of photocurrent left after 100 ms, but in all cases, it had decayed to the dark level within about 150–200 ms. So while it would be possible to extend the data slightly in the long time direction, this extension would not significantly alter the range of rate windows available.

Extending the data to include shorter rate windows is also problematic. The difficulty here lies in the fundamental experimental procedure. The experiment uses a broadband optical pulse. Unlike the case for an electrical pulse, it is not easy to turn off such a pulse rapidly. Since the source is broadband, electro-optical modulators and shutters which operate at a certain, specified wavelength, will not work. Thus we are restricted to using mechanical devices such as shutters and choppers. The latter are not convenient, since the light must be not only turned off rapidly (chopper spinning rapidly) but remain off for a considerable amount of time to allow the photocurrent to decay to the dark level (chopper spinning slowly). The particular broadband source used in the experimental arrangement described poses a second problem in that the light beam cannot be focused to a smaller spot size than the physical size of the source (about 5 mm diameter for our tungsten lamp). This restriction precludes focusing the beam to a size so small that even a relatively slow-moving chopper or shutter can cut it off rapidly. Although a small iris could be placed in front of the source, the total intensity of the light reaching the sample would be seriously reduced. It would thus take longer to optically saturate the sample. We have chosen, as a better (but still not ideal) solution, a electromechanical shutter as discussed above. Since it requires over a millisecond to close, we are unable to use time constants much faster than about 5 ms. Thus we cannot extend the rate window range significantly in the short direction either.

This relatively small range of rate windows severely limits the reliability of the data. The data shown in Fig. 6 reveal reasonably straight lines. But the data all lie so close together that it is difficult to be confident about the quantitative trap parameters derived from them. Thus, while data like those shown in Fig. 6 can be used for comparison purposes to determine which deep trap signatures are present in a particular sample, the slopes and intercepts in Fig. 6 are not, in themselves, accurate enough to determine precise information about the deep traps involved.

A further comment must be made concerning the data shown in Fig. 5 for undoped sample E. The high-temperature peak labeled peak No. 3 does not move when the time constant is varied. A similarly behaving peak at roughly the

same temperature was also observed in Cr-doped sample C as mentioned in the preceding paper. The presence of peaks whose PITS signal maximum does not change with time constant indicates that no meaningful trap parameters can be obtained from this part of the PITS signal.

One final note should be made in this section. It can be seen from Figs. 4 and 5 that no negative PITS peaks were observed. Negative peaks did not appear in any of the GaAs samples that we examined. Samples of CdTe and CdMnTe that we studied using the digital approach, however, sometimes did display such peaks. Thus the presence of negative peaks does not appear to be related to the equipment used or the approach taken.

## VI. DISCUSSION AND CONCLUSIONS

Several comparisons can be made using the data shown in Figs. 4–6. First, the results (obtained digitally) for sample D (Cr-doped) can be compared to the analog results for the same sample in Fig. 4. The trap signatures for sample D can then be compared to those for other Cr-doped material obtained by the analog method and shown in Fig. 8 of the preceding paper. In addition, the signatures displayed for sample D can be contrasted with those for the undoped sample E. Finally, these signatures can be compared to those found in the voluminous literature on deep levels in GaAs, and tentative identification of some of the trapping levels can be made.

To facilitate comparison of the trap signatures obtained for the Cr-doped samples using the digital approach with those obtained using the analog method, data taken by both methods for the same sample have been shown in Fig. 4. Two comments can be made concerning this figure. First, although the three major peaks observed by the digital approach are also seen in the analog data, the relative size of the peaks is dramatically different. This difference in peak height can be ascribed to different illumination conditions. Both measurements were made by passing light from a tungsten source through a silicon filter. However, the length of the light pulse was significantly shorter in the digital data. The effect of pulse length on the PITS signal has been discussed in some detail in the previous paper.[1] The second point that is evident from Fig. 4 is that the small peaks observed using the digital method are not present in the analog data. The greater sensitivity of the digital technique allows the observation of traps that are either close in activation energy to major levels, or of low concentration.

A further (although less direct) comparison between the two approaches can be seen in Fig. 6, where the trap signature lines from Fig. 8 of the preceding paper have been transferred. In order to achieve the reasonably good agreement shown, the lines had to be shifted to slightly lower values of $1000/T$. This indicates that the peaks observed using the digital system occurred at slightly higher apparent temperatures. This could be due to either the rather imprecise manner in which the temperature was measured using the analog system, or a systematic error in the digital system, *where the temperature sensor was not located on the sample itself*.

After allowing for this small temperature shift, the

agreement between the levels observed using the two different systems is quite good. Peak Nos. 1–4 are clearly visible in Fig. 6. Peak No. 5, ascribed to EL2 in the preceding paper, is not present in the data taken using the digital approach. Due to limitations on how high the temperature of the cryostat could be raised, we were not able to observe this trap with the digital system, although EL2 should certainly be present in both samples. The greater sensitivity of the digital approach is evident in Fig. 6, in that four additional peaks not seen using the analog approach were observed. These peaks are labeled A–D. It should be noted that all but one of these new levels were in the undoped material.

Peak No. 1 in Fig. 4 behaved rather strangely, in that the position of the maximum varied more strongly with time constant than expected. This behavior can be ascribed to the data showing the influence of two separate trapping levels with similar activation energies. That interpretation is strengthened when the data for this level is compared to the data for the undoped sample E in Fig. 6. At low values of the ordinate, this trap signature is about the same as that for level No. 1 in sample E, but at higher values the signature agrees with that of level B in the undoped sample. Both levels are probably present in samples D and E, but only resolved in sample E. The peak labeled B in Fig. 6 does not appear in the data shown for the analog approach in the preceding paper. However, other data from sample D, taken with the analog method, does indicate the presence of this trapping level.[9]

When the levels observed in the Cr-doped sample D are compared to those in the undoped sample E, it becomes apparent that while some are present in both, some traps appear in only one of the materials. The trapping levels observed and their parameters are listed in concise form in Table I. It should be noted that the assignation of specific levels to the traps shown in the data of Fig. 6 is tentative.

Treating first the levels that appear in both samples D and E, level B, which is present in both, but fully resolved only in sample E, appears to correspond to the level referred to as EL6, using the notation of Martin, Mitonneau, and Mircea.[10] This level, present in all of our samples, has been seen in most bulk GaAs and is usually ascribed to a point defect.[11] The parameters of the trap corresponding to peak No. 1, however, do not appear to coincide with any of the

TABLE I. List of the trap parameters observed in the Cr-doped GaAs sample D and the undoped GaAs sample E, as calculated from the results plotted in Fig. 6. For each trap observed, the activation energy and parameter A from Eq. (1) are shown. Also listed are tentative identifications for each of the levels.

| Trap observed | Activation energy (eV) | Parameter A | Tentative ID |
|---|---|---|---|
| A | 0.23 | $9.4 \times 10^{-6}$ | EL8 |
| B | 0.28 | $1.1 \times 10^{-6}$ | EL6 |
| No. 1 | 0.21 | $1.1 \times 10^{-3}$ | ? |
| C | 0.36 | $7.7 \times 10^{-7}$ | $Cr^{+4}$ |
| D | 0.48 | $6.1 \times 10^{-8}$ | EI1? |
| No. 2 | 0.58 | $2.0 \times 10^{-8}$ | EL3 |
| No. 3 | 0.59 | $6.0 \times 10^{-7}$ | EL12 |
| No. 4 | 0.75 | $3.9 \times 10^{-8}$ | HL2? |

known levels usually observed in GaAs. Trap No. 2 in Fig. 6 fits quite well with the reported data for EL3, which is also seen in most bulk GaAs. And although peak No. 3 in the undoped sample E is problematic, in that the position of its maximum signal does not change with time constant, its position in Fig. 6 associates it with the level observed in the Cr-doped sample D. This level may be due to the presence of HL9, but is more likely connected to the level known as EL12. Originally this trap was thought to be due to the presence of oxygen,[12] but later work showed that the oxygen peak occurred at a somewhat higher temperature.[7]

Two peaks appear only in the Cr-doped sample D. Level C appears in some but not all Cr-doped samples. Lang and Logan have suggested that this level is due to the presence of copper,[13] but we feel that it must be due to the chromium in the material. An alternative explanation is that this level is due to a transition from the $Cr^{+3}$ state to the $Cr^{+4}$ state.[14] This interpretation is supported by electron spin resonance (ESR) experiments showing the presence of $Cr^{+4}$,[15] and two-beam photoconductivity measurements,[14] both of which show reasonably close optical excitation thresholds.

The other peak appearing only in the Cr-doped sample, level No. 4, occurred near both the rate window and temperature limits of the apparatus. Close examination of the data shown in Fig. 5 for undoped sample E may indicate the presence of this peak as a high-temperature shoulder on the peak corresponding to level No. 3. However, its magnitude is not great enough to ascertain any trap parameters. The small size of this peak, even in sample D, and its position near the limit of our instrumentation makes any identification speculative. The signature of this level is similar to that for both HL2 and HL10, using the notation of Mitonneau, Martin, and Mircea.[16] HL2 has been ascribed to a native defect of some kind,[13] and HL10 may be due to vanadium.[16] The defect explanation appears more likely. It should be noted that this level has been observed in some Cr-doped samples using the analog approach of the preceding paper, although never strongly. Thus its identification remains speculative, at best.

Two peaks appeared in the PITS spectrum of sample E that were not matched by peaks in sample D. The level whose peak is labeled A in Fig. 6 appeared as a shoulder on the EL6 peak. Since it was never completely resolved, its signature is difficult to interpret. We believe that this peak may be due to EL8, a native defect often seen in bulk GaAs material.[12]

The peak labeled D in Figs. 5 and 6 is a major one that appeared in only the undoped sample E. Although its signature does not correspond very well to any of those tabulated in the literature,[10,16] it is closest to EL4 and EI1. Since EL4 has been observed only in molecular-beam epitaxy (MBE) material,[10] we assume that D is due to EI1. This trapping level is probably due to an impurity of unknown nature in the material. This inability to reliably identify even some of the strongest peaks observed is not atypical, and is indicative of the frustration often inherent in using the PITS technique.

We have described a relatively simple experimental system designed to study the deep trapping levels present in semi-insulating materials. Studying the decay of photocurrents (PITS) can provide a quick, relatively easy way to obtain information concerning the traps that may be present in a sample. However, several problems exist, both with the analysis of the data, and with the experimental technique itself, that limit its usefulness and applicability. Although the analysis assumes a simple exponential form of decay, the actual form tends to be either nonexponential or the sum of several exponentials. If we ignore this problem and analyze the data anyway, we are confronted with a limited range of data that cannot be easily extended in either direction. The information extracted from this limited data, then, is prone to limited accuracy and reliability.

The PITS technique does provide information, however, on material that is highly resistive, and thus difficult to analyze using other methods. That this knowledge is not quantitative limits the use to a survey technique, but certainly does not proscribe it altogether. We have found that by comparing our results with data gathered from low-resistivity materials using different techniques, we are able to, at least qualitatively, determine what deep-level traps are present in semi-insulating samples in significant concentration. While applied here to bulk material, PITS has been, and should continue to be, applicable also to high-resistivity layers.

## ACKNOWLEDGMENTS

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