CLEVELAND STATE UNIVERSITY

Final Technical Report

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The major purpose of this grant was to study the fundamental properties of semiconductor materials and to relate them to the performance of these materials when fabricated into detectors. In this research we have been able to make such a relationship between the minority carrier lifetime in the bulk of the material and the charge collection efficiency of the detector. A rough draft of a paper on the lifetime measurements which is being submitted for publication is included as Appendix I of this report.

The minority carrier lifetime research is of importance to any group wishing to fabricate semiconductor radiation detectors. To understand this point, it is necessary to summarize previous research.

The measurement of minority carrier lifetimes has been standardized in 1961 in an IEEE Standard.[1] Typically, a light source having a short duration high intensity flash illuminates one face of a semiconductor crystal. Electrodes are plated onto the flat faces of the crystal, and a small electric field is applied between the electrodes. Minority carriers, excited into the conduction band by the flash of light are collected at one of the electrodes. This current pulse is then amplified by a DC amplifier and displayed on an oscilloscope.

The minority carriers which have been excited into the conduction band will recombine and leave the conduction band. Since the recombination rate at any time depends on the number of carriers present at that time in in the conduction band, the number of carriers decays exponentially with time, that is

$$N = N_o e^{-t/\tau}$$

where τ is the minority carrier lifetime characteristic of the material. The pulse displayed on the oscilloscope is an exponentially decaying pulse. The lifetime can then be obtained directly from the semilogarithmic plot of this pulse.

A serious problem has always plagued this measurement. Near the surface of the crystal, the electric fields are difficult to specify since there are unfulfilled covalent bonds, and the electric field produced across the electrodes is a fringing field. Moreover, the light source may have a spectrum rich in light frequencies which will not penetrate the crystal but may excite carriers near the surface.

This particular point can be easily seen in two of the figures in the paper in Appendix I. The first graph, Figure 2, is a semilogarithmic plot of the minority carrier decay near the surface. The second graph, Figure 3, is a semilogarithmic plot of the minority carrier decay in the bulk. The "surface lifetime" shows only one lifetime of about 400 microseconds while neither of the two lifetimes associated with decay in the bulk have this value. Furthermore, no evidence of either of the bulk lifetimes can be seen in the surface lifetime. The minority carrier decay near the surface dominates all other decays as is evidenced in Figure 2.

Two approaches have been taken in past research to overcome this dominance by carrier decay near the surface. The first is to interpose another slice of the crystal between the light source and the crystal. The purpose of this is to cut out that portion of the light spectrum which most easily excites carriers near the surface. While this approach has been relatively effective compared to no filter at all, a lifetime associated with recombinations near the surface will still be mixed in with the lifetime(s) associated with recombinations in the bulk. Thus, the graph shown in Figure 3 of the paper in Appendix I would display a third lifetime if the surface lifetime could still be observed. Lifetimes of 285, 400 and 500 microseconds would yield a plot that would not be easily untangled.

The second approach taken in other research has been to control the dimensions of the sample.[2] The diffusion relation can be used to obtain an equation for the effective or observed lifetime in terms of the dimensions of the sample and the surface recombination velocity. If samples of different dimensions are used, then this equation can be solved for the bulk lifetime.

The difficulties with this approach are apparent. There is a strict demand that the lifetime be the same for all samples used. While this may be true over some limited region of the crystal, the growth process is usually not uniform and such an assumption is suspect. Secondly, the surface treatments must be identical. As we have shown in one of our status reports,[3] the surface lifetime is very sensitive to variations in surface treatment and is time-dependent. Moreover, the final equilibrium lifetime is not only dependent on the kind of surface treatment, but also the number of treatments. Thirdly, the crystal whose lifetime is measured is not the one that will be used as a detector since the dimensions used in measuring a lifetime are generally inappropriate for detectors. Finally, there is an implicit assumption that there is only one lifetime that corresponds to the bulk. If there is more than one lifetime involved, the equations are extremely difficult to solve. However, as can be seen from Figures 2 and 3 of the paper in Appendix I, the bulk lifetime for this particular crystal had two components. For detector evaluation this point is critical. If there are two lifetimes that can be observed in the bulk of the material, then conclusions can be drawn about the performance of the crystal when fabricated as a detector.

This important result is related to charge collection efficiency. In most references[1] a very short lifetime is usually associated with the surface decay. When a detector is fabricated, is is relatively easy to collimate the beam of incident particles. Any effects related to the outside edge of the crystal, such as a short lifetime, can be avoided. These edge effects are usually observed when particles are incident on the detector as pulses whose amplitude or risetime is substantially attenuated. From Figures 2 and 3 of the paper in Appendix I, the shortest lifetime is characteristic of the bulk. In order to see the effect of this on charge collection, spectra were taken with different detectors. In all cases the internal conversion spectrum of Bi^{207} was measured with a detector. The beam was collimated so that only half of the crystal area could detect particles. As a typical set of results, Figures 4 and 5 show two spectra taken with two different detectors. Spectrum A was recorded with a detector fabricated from a crystal having only one lifetime of 600 microseconds associated with the bulk. Spectrum B was recorded with a detector made from the crystal whose lifetimes are shown in the paper in Appendix I.

The major difference in the two spectra is an attenuation of pulse height and a failure to record all of the counts at a particular energy in Spectrum B. This phenomenon has been repeated with many different crystals from three different manufacturers, NPC, Dow-Corning, and Wacher. If a very short lifetime is observed in the bulk, particularly when there is a longer lifetime present, then the detector fabricated from the crystal will display poor charge collection efficiency. It should be noted that it is possible to determine this before fabrication of the detector from any particular slice of material by using the technique described in the paper in Appendix I.

We feel that this represents a major advance in the art of detector fabrication. It is the first time that the performance of a detector has been related to the measurement of any fundamental parameter.

The second aspect of this research was concerned with the fabrication of detectors from intrinsic germanium. This work was completed earlier and reported in the status reports for the periods May 1, 1971 to July 31, 1971 and August 1, 1971 to October 30, 1971.

FIG. 4 SPECTRUM A

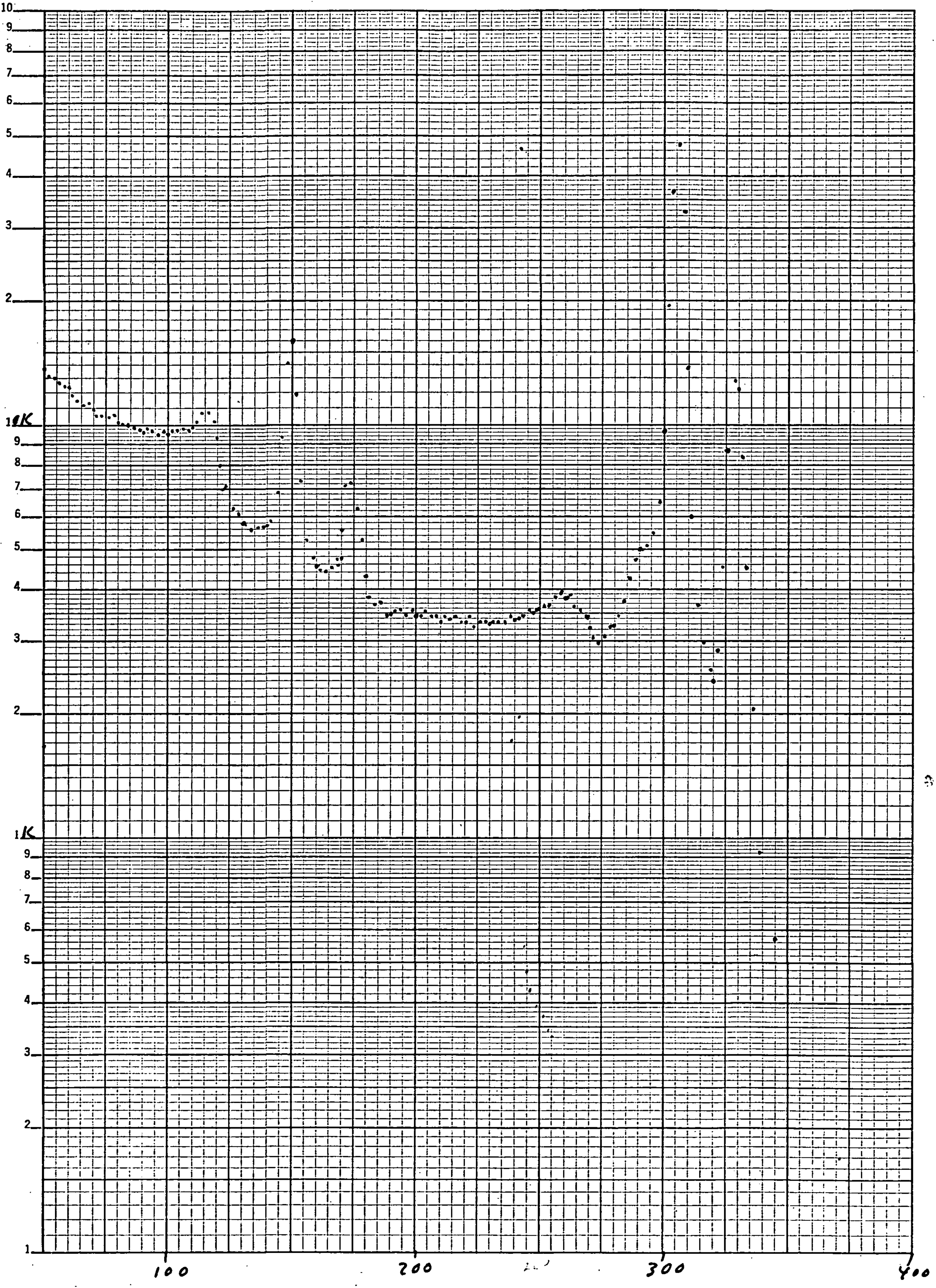
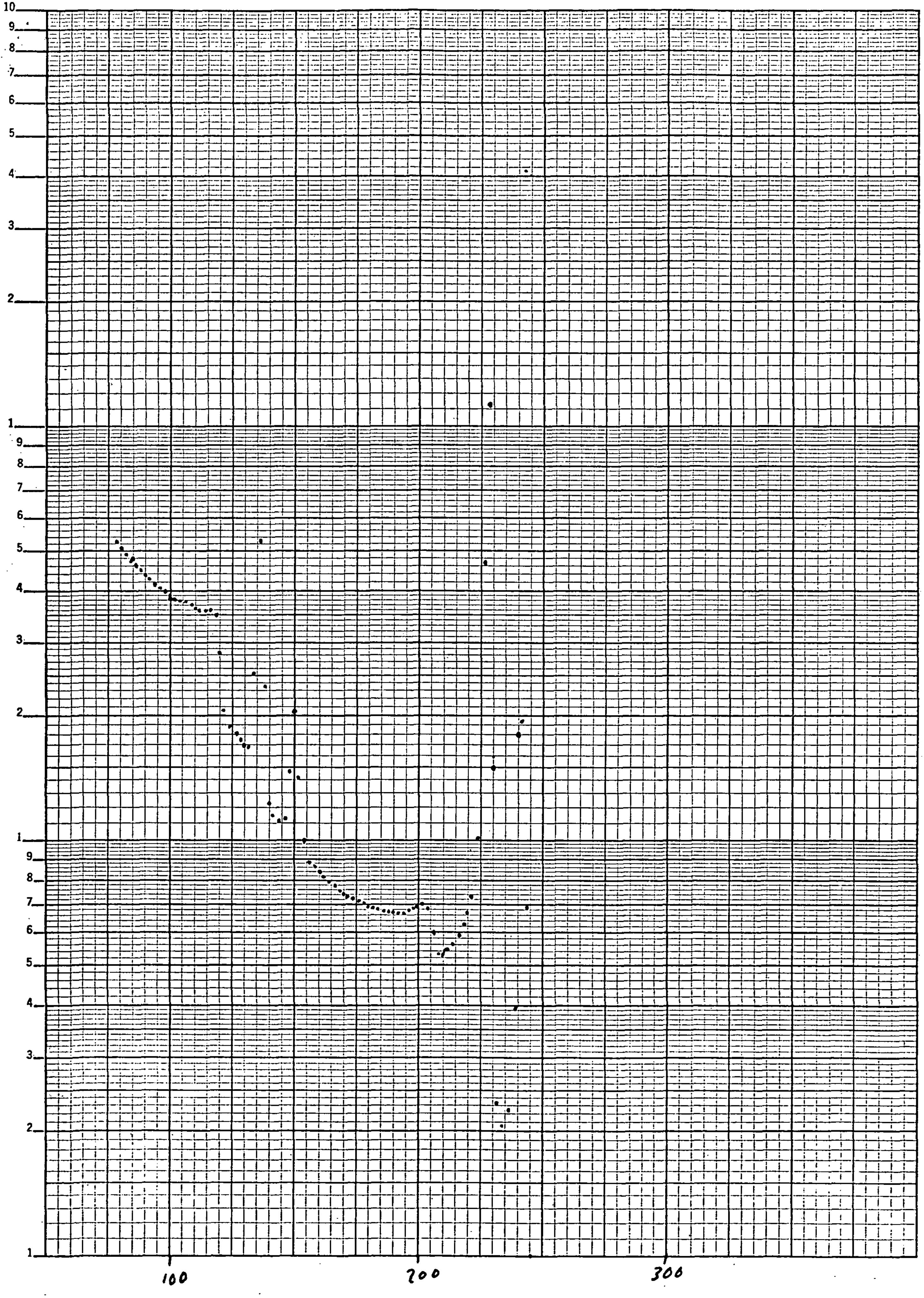


FIG. 7 SPECTRUM D



References

1. IRE Standards on Solid-State Devices: Measurements of Minority-Carrier Lifetime in Germanium and Silicon by the Method of Photoconductive Decay. Standard 61 IRE 28.S2.
2. Solid State Physics, Part B, K. Lark-Horovitz and Vivan A. Johnson, editors, page 96.
3. Status Report for the period August 1, 1969 to October 31, 1969.

APPENDIX I

Lifetime Meaurements in Silicon by Photoconductive Decay*

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The literature of photoconductive lifetime measurements in silicon is rich and extensive and has been summarized by Bremski in a review article.[1] Among the problems yet to be solved, however, is that of separating the bulk and surface lifetimes. So far, this problem has been dealt with mathematically. In this paper an experimental method of achieving this separation is discussed.

Basically, any measurement of minority carrier lifetimes must distinguish between the lifetime of carriers excited near the surface and the lifetime of carriers excited in the bulk. A short burst of light is used to excite non-equilibrium carriers in a sample across which an electric field is applied. The excess carriers produce an initial change in the conductivity which returns to the equilibrium value when the light is turned off and the carriers recombine. The exponential decay can be expressed in terms of a lifetime characteristic of the material.

If the light is very penetrating, the number of carriers excited near the surface will be small. However, the light sources used must have a broad spectral range if all carriers, even those from impurities, carriers near the surface which may be excited by that spectral region which contains non-penetrating light may be quite numerous and may tend to dominate in the current pulse seen at the output.

In order to filter out the spectral region which would excite carriers near the surface, a filter of the same material as the sample is often interposed between the sample and the light source.[2] Such a filter will not completely eliminate surface excitation since there is a finite probability that the carriers will be excited near the surface even by very penetrating rays. The current pulse seen at the output will still display this short lifetime characteristic of the surface since the number of carriers decaying with a long lifetime will be spread out over a much longer period of time.

The technique described in this paper uses a portion of the crystal itself as a filter. If the crystal appears as shown in Fig. 1, carriers produced in volume A of the crystal will be collected at electrode C and carriers produced in volume B will be collected at electrode D. This phenomenon in which the carriers follow very closely the electric field lines has been used before in position sensitive measurements in radiation detectors, but has not been applied to lifetime measurements.

In the crystals used, region A is an annulus surrounding a central cylinder B. Since the crystalline structure is preserved, the cylinder B has no surface insofar as light incident at right angles as shown in Fig. 1 is concerned. Therefore, lifetime measurements using the current pulse appearing at electrode D must be solely bulk lifetime measurements while those appearing at electrode C will be a mixture of surface and bulk lifetimes.

The technique has many advantages over a standard methods[2]:

1. This technique allows non-destructive lifetime measurements of sample slices or ingots. The ingots need not be shaped or processed to a particular size as is usually done.

2. A true bulk lifetime measurement can be obtained directly. The portion of the sample in which this measurement is made is completely

surrounded by material and does not have any surface. It is not necessary to interpose a filter between the sample and the pulsed light source in order to reduce that part of the light spectrum which would excite carriers near the surface since these carriers are now collected at a different electrode.

3. It is not necessary to determine the surface lifetime by mathematical analysis of lifetimes measured with the light incident on different surfaces.

4. Since the bulk lifetime is determined directly, this lifetime can be used in conjunction with the measurements on the outer ring to determine surface lifetimes. Variations in the surface lifetime with variation in surface treatment can also be seen.

The electrodes consisted of gold evaporated onto the lapped faces of the crystal. Conductivity measurements were made to ensure that these contacts were ohmic. The rings were formed by selectively removing the gold after protecting regions with Kodak KPR photoresist. The electric fields across the crystal was established by adjusting conventional transistor constant current circuits, one for the inner circle and the other for the outer ring, until the potentials on the inner circle and the outer electrodes were the same. The important feature here was the very high AC impedance at the collector of the transistor. When one region was bypassed with a 1000 mfd capacitor to ground, no signal could be observed on the oscilloscope from the associated electrode. On the other hand the channel resistance between the two regions was sufficiently high that the signal from the other electrode was unaffected. This capacitor was connected so that it could be easily switched from one region to the other.

The signal from the electrodes was DC amplified and DC coupled to the to the oscilloscope. Unwanted RC time constants were thereby avoided. The sweep on the oscilloscope was frequently calibrated during each run with a Tektronix Time Mark Generator.

It was found to be essential to trigger the oscilloscope electronically before the pulsed light source illuminated the sample. This produced in the sweep a precursor baseline establishing the zero baseline for a particular pulse. Without such a precursor, it is necessary to fit the data with an exponential curve having an offset. With the precursor a simple least squares fit of the logarithm of the pulse height to the time coordinates is sufficient. Since more than one lifetime may appear in the pulse, the simplification is essential.

The pulsed light source for most of the measurements was a General Radio Strobotac. It can be reliably triggered electronically and the pulse width of the light pulse as measured with a photomultiplier tube is 1 microsecond. Since the lifetimes measured here were of the order of 100 microseconds or more, this pulse width is quite adequate.

Results

The main purpose of this technique was to avoid the complexity of analyzing data in which two lifetimes whose decay rates and amplitudes are unknown may be present. The results of the measurements utilizing the techniques outlined in this paper are shown in Figs. 2 and 3. In the bulk lifetime is 580 microseconds. A least squares fit was performed in each case on successively larger numbers of points beginning with the last five data points and proceeding backwards. The lifetimes were in agreement except when the first 20% of the pulse was included.

It should be noted that the bulk lifetime has two components: a relatively long lifetime of 580 microseconds and a shorter one of 240 microseconds.

The discrepancy in these two lifetimes is a factor of 2.4 which permits them to be separated as can be seen in Fig. 3. However, without this technique, the surface lifetime of 400 microseconds would also be included in the decay curve. Three lifetimes would be nearly impossible to extract from the data since the values for the lifetimes are quite close together. It is also apparent from the data shown here that the surface lifetime decay dominates in the data. Thus, in Fig. 2, there is no evidence of either of the lifetimes of Fig. 3, although the plot is not strictly logarithmic near the beginning of the pulse. Either the lifetimes vary significantly in different regions of this crystal, or else carriers decay near the surface primarily with lifetimes characteristics of the surface. Further data indicates the latter result is correct, since the lifetimes measured at the surface can be changed by a factor of two by application of organic solvents and other treatments to the surface of the crystal. Moreover, these lifetimes are time-varying and irreproducible. Thus, spraying the surface with acetone will reduce the lifetime at the surface by nearly a factor of two, but after an hour the lifetime has returned to its original value. Further treatments with acetone will again reduce the lifetime but rarely by the same factor as the first treatment. It therefore appears that the lifetime measurement in the outer region is truly a surface lifetime.

References

1. G. Bremski, Proc. IRE, 46(1958)990.

2. IRE Standards on Solid-State Devices: Measurements of Minority-Carrier Lifetime in Germanium and Silicon by the Method of Photoconductive Decay. Standard 61 IRE 28.S2

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Figure Captions

Figure 1. Electrode configuration for lifetime measurement. C is an annular ring electrode while D is a circular electrode in the center of the crystal face.

Figure 2. Semi-logarithmic plot of data taken from the pulse appearing at the annular ring electrode. The straight line fit to the points is characteristic of a 400 microsecond lifetime.

Figure 3. Semi-logarithmic plot of data taken from the pulse appearing at the central electrode. The points marked B have been determined by subtracting the straight line fit to the last 15 points from the data. The two straight line fits are characteristic of lifetimes of 580 and 240 miroseconds.

Fig. 1

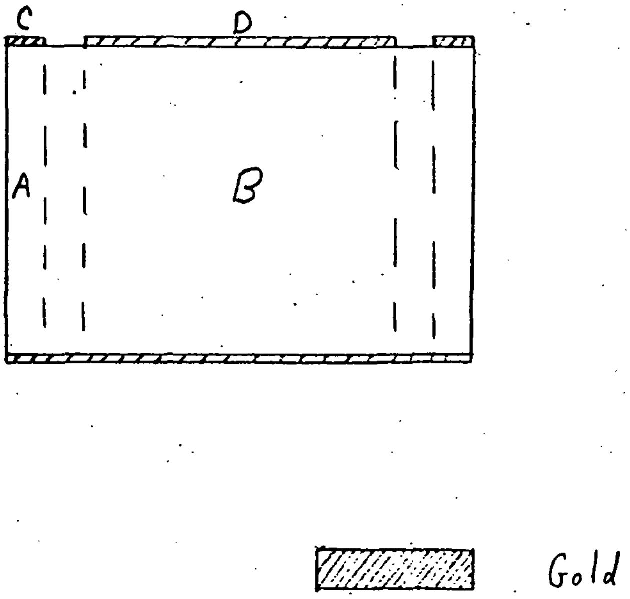

FIG. 2

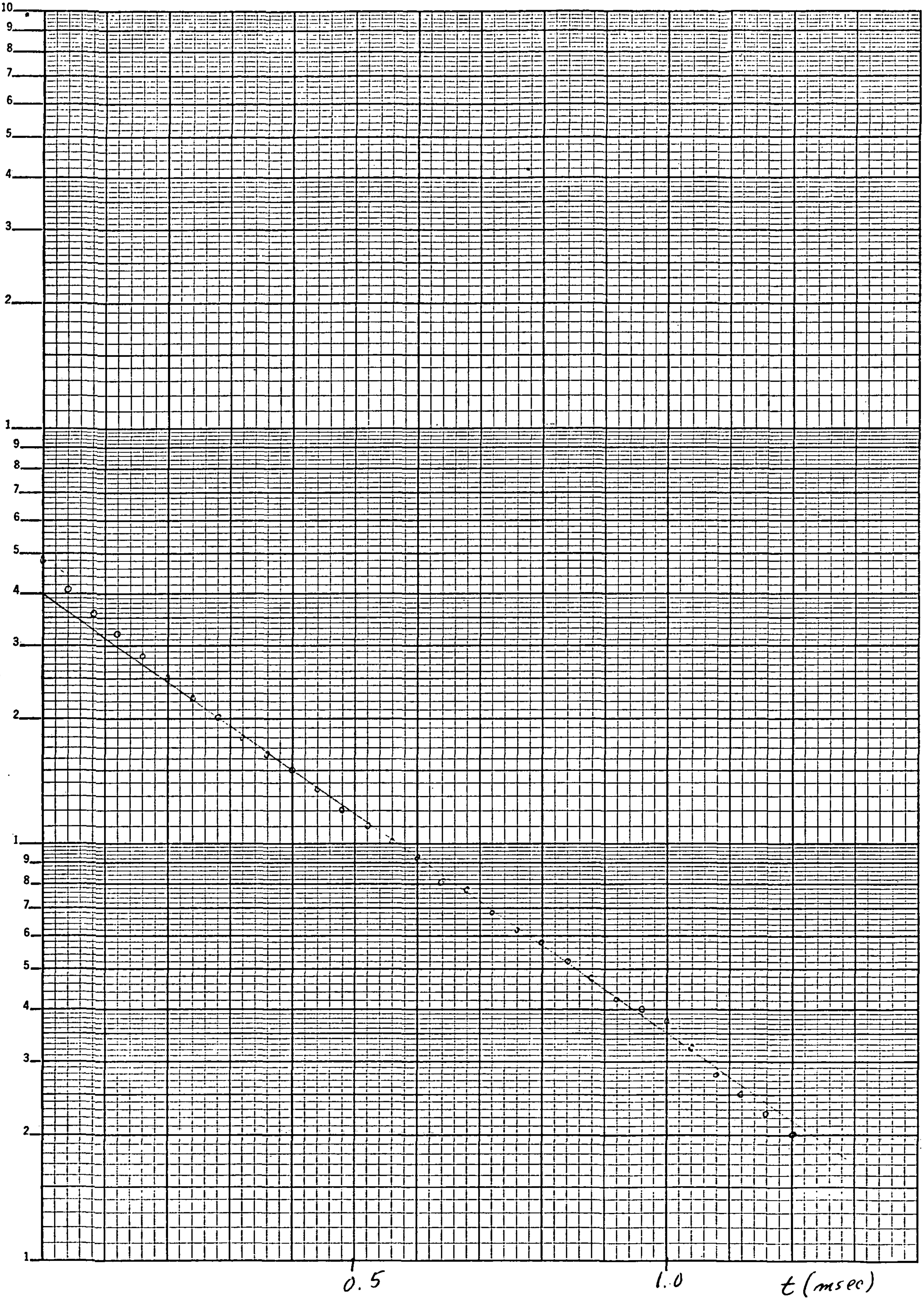

FIG. 3