Proceedings of the Iowa Academy of Science

Volume 57 | Annual Issue Article 43

1950

Diamond Conduction Counters

Robert K. Willardson
Iowa State College

Diamond Conduction Counters*

ROBERT K. WILLARDSON

Introduction

The intensity of radiation of high energy particles or photons is usually measured by allowing these radiations to ionize the gas molecules in a gas-filled chamber (3). The ions are collected on electrodes and the ion current indicates the intensity of the radiation. Single fast particles give a sharp pulse of ion current. Attempts have been made to use solid bodies in place of the gas-filled chamber (7, 12, 14). The radiation ionizes the solid in a manner similar to that for the gas. Because of its high energy a single particle creates in the crystal a large number of freely moving electrons and positive holes. These electrons and positive holes move without any simultaneous transport of atoms. Hence, the rise time of the electrical pulse obtained from a crystal can be one hundred times less than that of the corresponding pulse created by a single particle in a gas-filled chamber. Because a crystal conduction counter has such an extremely fast counting mechanism, various types of crystals are being investigated for possible use. We have investigated the counting properties of diamond in some detail.

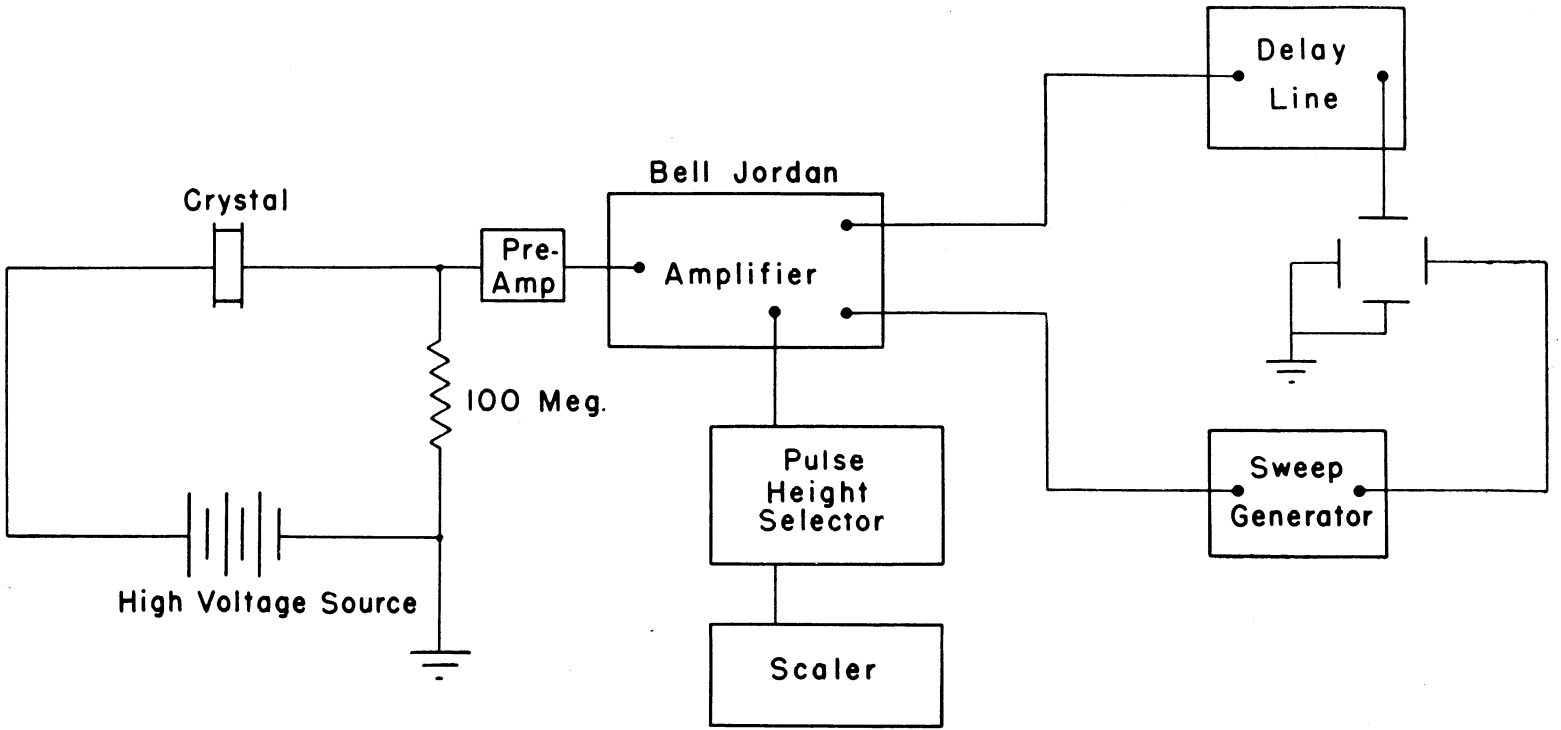
Experimental

A block diagram of a crystal conduction counter is shown in Fig 1. The size of the voltage pulse depends on the energy of the incident particle, the field applied to the crystal, and the capacitance to ground of the input circuit. To obtain maximum pulse height it is necessary to have the input capacity as small as possible. The input capacity to our preamplifier is about ten pico farads. Using field strengths of 10,000 volts/cm. we obtain pulses of about one millivolt when one mev. particles enter the diamond. A high gain amplifier is needed to convert such a small pulse into one large enough to operate a scaling circuit. The noise level of the present linear high gain amplifiers is about twenty microvolts, so only particles with energies of over about 20,000 ev. of energy can be individually counted.

When counting gamma rays with a diamond conduction counter, the number of counts per minute obtained depends on the height

* This work was done in part in the Ames Laboratory of the Atomic Energy Commission.

Contribution No. 100 from the Institute for Atomic Research and Department of Physics, Iowa State College, Ames, Iowa.



CRYSTAL CONDUCTION COUNTER

Fig. 1. Block diagram of a crystal conduction counter.

of the voltage pulses. The height of the voltage pulses in turn depends upon the applied field strength. An experimental curve showing the number of gamma rays counted as a function of the applied field is shown in Fig. 2.

Space Charge Effects

A complete collection of all the freely moving charges in a crystal conduction counter is usually impossible because many of these charges are trapped by impurities or defects in the crystal lattice. These trapped charges form a space charge field. The magnitude of the space charge field depends upon the separation of the electrons and holes at the time they are trapped as well as upon the number of trapped charges. The average distance δ that an electron moves is given by $\delta = vET$ where E is the field strength, v is the mobility, and T is the average time before the charge is trapped. It can be shown by theoretical considerations that the magnitude of the voltage pulse is V eff. $= \frac{N_o e}{c} \frac{\delta}{d}\left[1 - \frac{\delta}{d}\left(1 - e^{\frac{-d}{\delta}}\right)\right]$ where N_o is the total number of secondary electrons freed by the

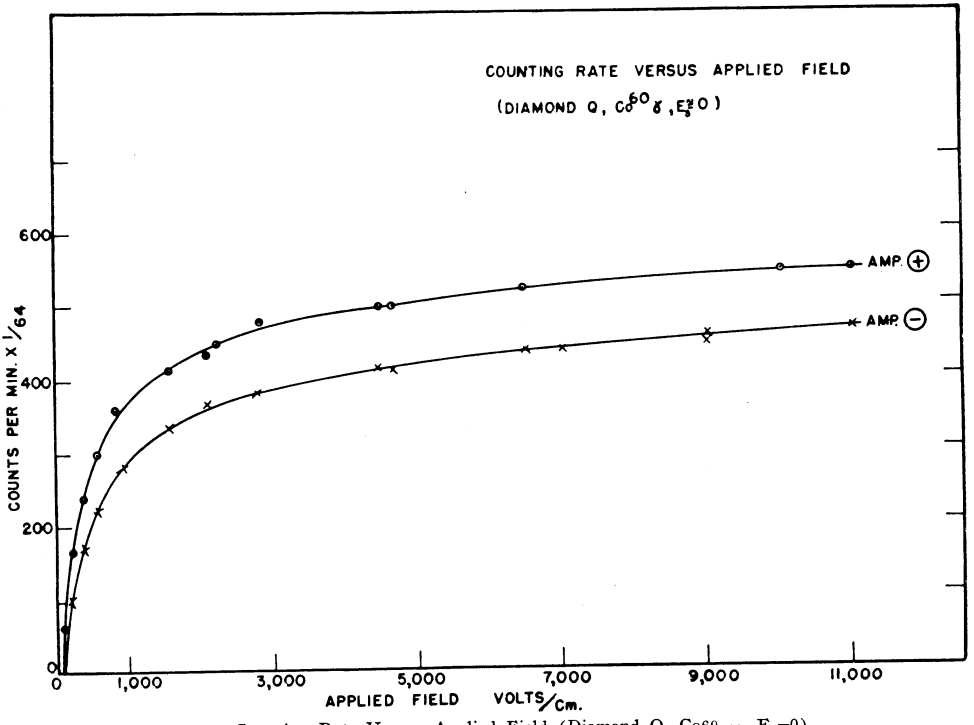


Fig. 2. Counting Rate Versus Applied Field (Diamond Q, Co^{60} γ, E_s=0)

ionizing particle, and d is the electrode separation. The equation indicates that the pulse height depends on δ which has been shown to be a function of the field strength. As more particles are counted the space charge field increases, and a decrease in the effective field results. The decrease in effective field causes the counting rate to decrease as a function of counting time (Fig. 3). If the external

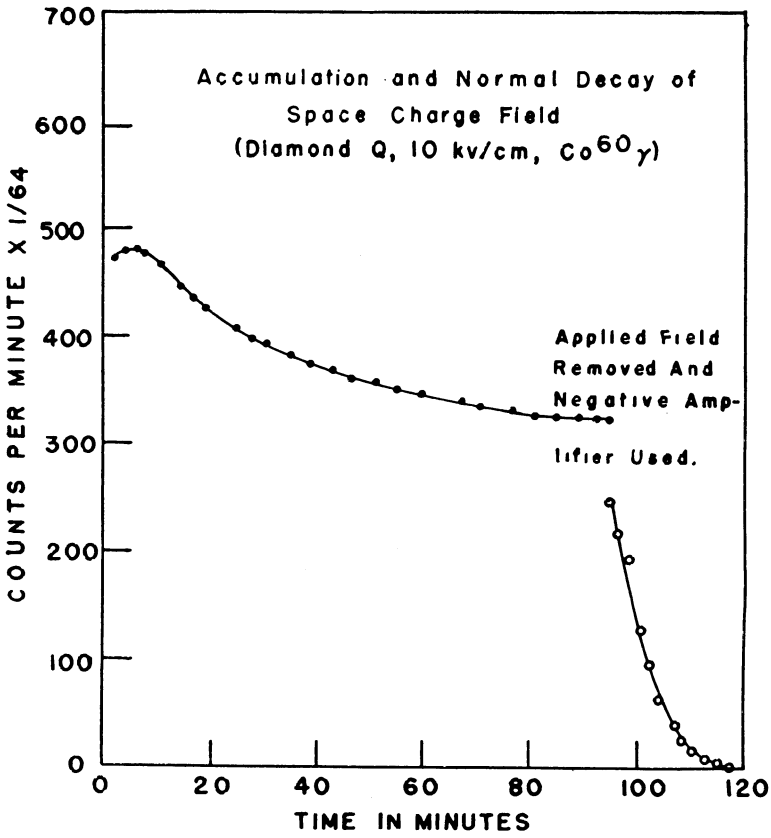


Fig. 3. Accumulation and Normal Decay of Space Charge Field (Diamond Q. 10 kv/cm, Co60 γ)

field is removed after the diamond has been counting for some time, the space charge field can be used for counting (Fig. 3). In this case the polarity of the voltage pulses is reversed.

Space charges can be removed from the traps by irradiating the diamond with monochromatic red light (13). When the light is removed the space charges accumulate and the counting rate decreases (Fig. 4).

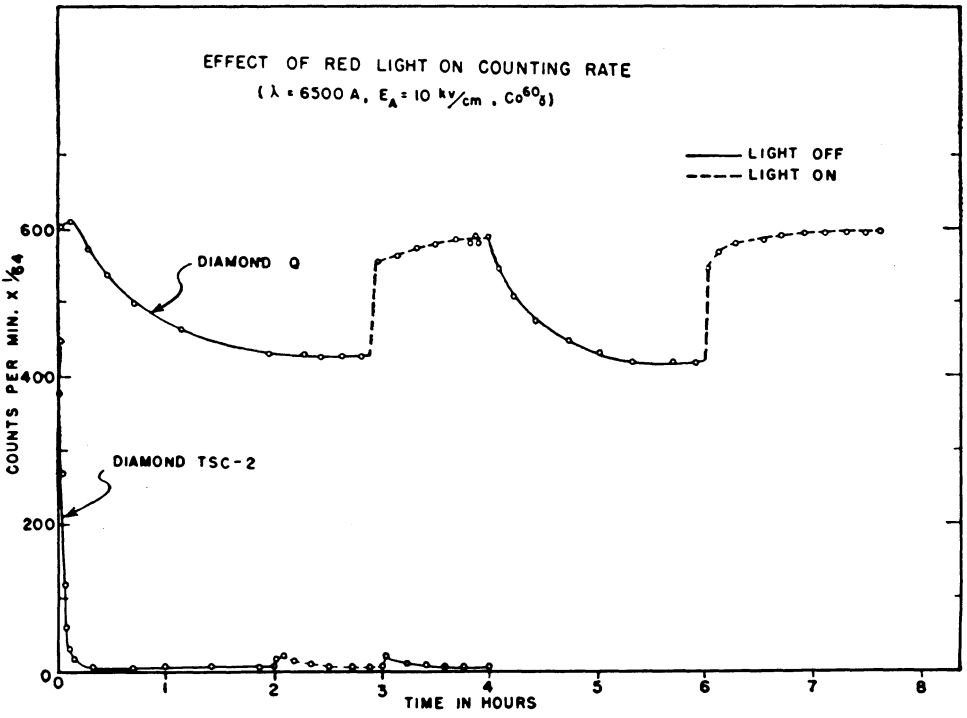


Fig. 4. Effect of Red Light on Counting Rate ($\lambda = 6500$ A, $E_A = 10$ kv/cm., Co^{60} γ)

Activation of Diamonds

If the counting rate of a diamond is observed as a function of time, it usually decreases due to space charge effects, then after reaching an equilibrium increases to a constant value which may be as high or even higher than the initial rate. When this high constant counting rate is reached, the diamond may be thought of as being in an activated condition (13). In the case of diamond Q it takes about twenty hours for the counting rate to increase to ninety percent of its final value. A few minutes exposure to monochromatic violet light or a heterogeneous mixture of light containing violet light will reduce this time to about one hour (Fig. 5). If a light treatment is used a sharp dip in the counting rate is observed immediately after the light is applied. This dip is attributed to the additional space charge resulting from the trapping of photoconductive charges. The high constant counting rate obtained with diamond Q in the activated state has been maintained over a period of two hundred and fifty hours. After the activated condition is obtained the source of gamma rays can be removed, and when the source is replaced hours or days later the high constant counting

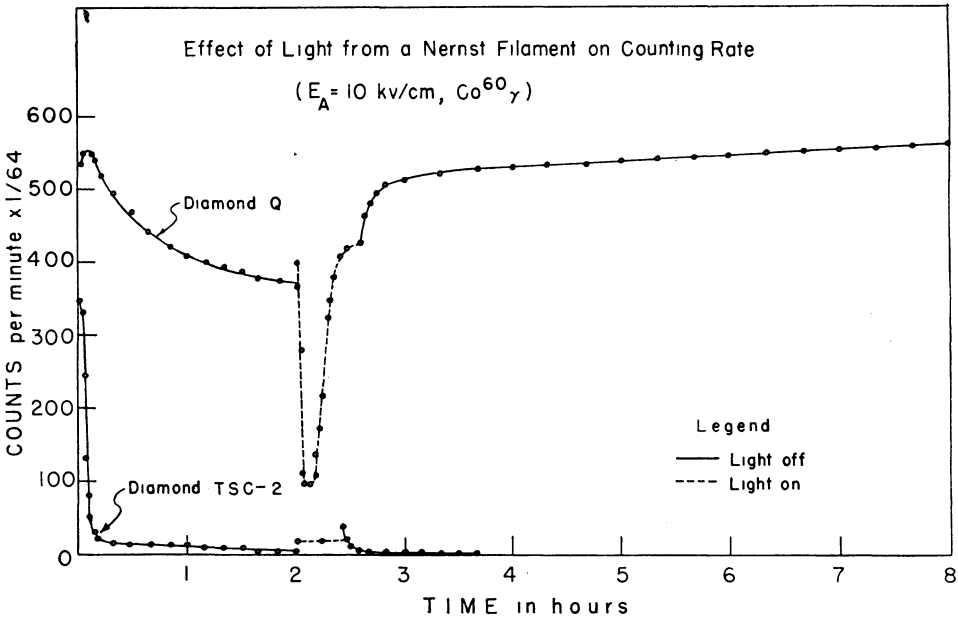


Fig. 5. Effect of Light from a Nernst Filament on Counting Rate ($E = 10$ kv/cm, Co^{60} γ)

rate is obtained immediately. If the external field is removed for an hour, during which time the crystal is bombarded with gamma rays, diamond Q will return to its initial condition. The activation process must then be repeated.

Some diamonds do not return entirely to their initial state after once being activated. Other diamonds have an initial condition which corresponds to the state of diamond Q after it has been counting for some time.

Optical Properties

Some diamonds count gamma rays with a high efficiency while other diamonds appear not capable of counting or at the most count very few of the incident photons. The reason for this may be due to very severe space charge effects as suggested by the fact that some counting diamonds exhibit much greater space charge effects than others, i.e. diamond TSC-2 as compared to diamond Q in Fig. 4. The wide variation in the gamma counting property in different diamonds could probably be explained more satisfactorily if a correlation could be found between the counting and the variation in optical properties of diamond.

Kallman (7) has reported unusual counting properties in fluorescent cadmium sulfide crystals, and Hofstadter (6) has suggested

a possible correlation between the ability of diamonds to count and their luminescence. For the diamonds tested no correlation is apparent (Table 1).

The birefringence patterns of our diamonds have been observed and photographed. The variation in strain patterns had no obvious relationship to counting ability.

Friedman, Birks and Gauvin (4) have attempted to correlate ultraviolet transmission data with the gamma counting property. The results of their investigation indicate that gamma counting diamonds are ultraviolet transparent (Type II). Our results do not substantiate this

The two to sixteen micron infra red absorption spectra of diamond has been investigated in great detail (2, 10, 11). Diamonds which show an absorption peak at eight microns were classified Type I by Robertson, Fox, and Martin. Those which did not have this peak were called Type II. Our investigations in the two to sixteen micron region perhaps indicate a slightly more than chance correlation between the absence of the eight micron peak and good counting diamonds.

A broad infra red absorption band extending from nineteen to twenty-three microns with a peak at twenty-one microns has been found. This absorption peak is not present in all diamonds (Table 1). The absence of the twenty-one micron absorption peak seems to be characteristic of good counting diamonds, but exceptions to this generalization are conspicuous

In the entire two to twenty-six micron region the general infra red absorption has a tendency to be greater for diamonds having the gamma counting property.

The diamonds were irradiated by an intense (10^{-2} gram-cal/cm. sec.) light of wavelengths 4000 to 7000 A and by a quartz-mercury lamp. The photoconductive currents were measured and found to be larger for some of the better counting diamonds. However, the correlation as a whole is not good. Type II diamonds exhibit greater photoconductive currents than Type I (11). An unusually large photoconductive current is obtained from diamond C.

Interpretation of Counting Properties

A possible energy band diagram for diamond is shown in Fig. 6. Work by McKay (8) and Ahearn (1) suggests a separation of the filled band and the conduction band of about ten ev. Calculations made from optical data give about seven ev. An approximate relation between the half-life of a charge in a trap and a trap depth

$$B/\sigma = 2\pi m\ (KT)^2\ h^{-3}\ (6\pi)^{1/2} \exp(-E/KT)$$

(in which B is the probability per second that an electron escapes from the trap, σ is the capture cross section of the trap for thermal electrons, and E the depth of the trap) can be used to determine E, the depth of the trap. Using Ahearn's experimental data to determine B/σ, Newton (9) has calculated the traps to be ¼ to ¾ ev. in depth. The level between the filled and conduction bands is suggested by the fact that violet light speeds up the activation process and the photoconductive current is larger when light of the longer wavelengths is used. The negative Hall coefficient for heterogeneous quartz-mercury light photoconductivity places this level nearer the conduction band. The violet light activation effects give the distance as about three ev. from the conduction band.

We have seen that a diamond may become a good stable counter in spite of the existence of space charge. The diamond is apparently in some sort of activated condition. This unusual phenomenon that we have discovered is not completely understood; however, the following mechanism is suggested as a likely possibility. It is postulated that excited levels, which are normally full, exist 2.5 or 3 ev. below the conduction band (see Figure 6). Violet light or gamma rays (but not red light) can partially empty these levels. The electrons so raised to the conduction band account for the

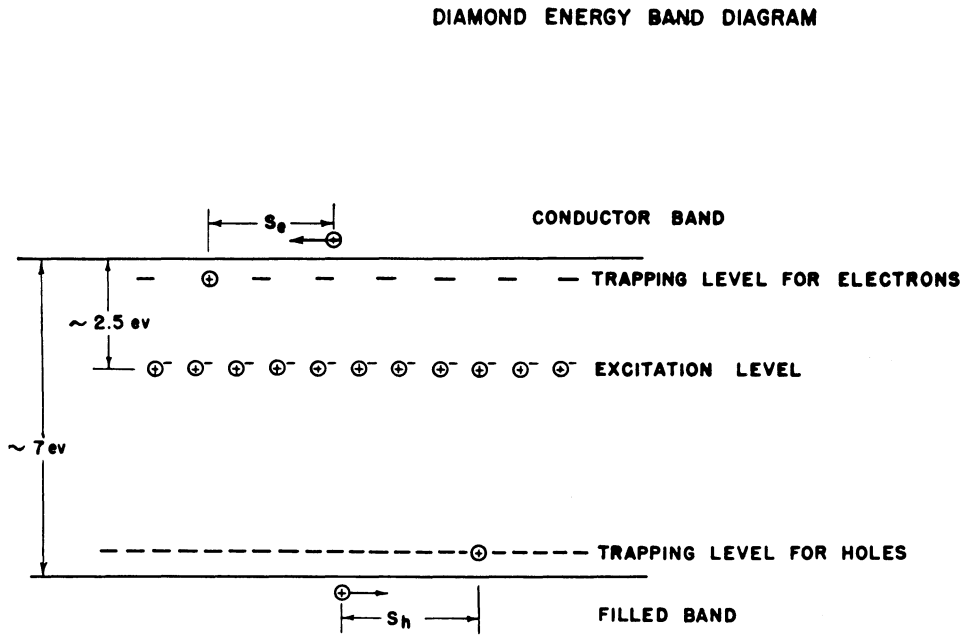


Fig. 6. Diamond Energy Band Diagram

Table 1

Optical and Counting Properties of Diamond

Diamond	Weight	Thickness	Gamma Counting Property	Blue Luminescence	Ultra Violet Trans. Limit	Infra Red Adsorption Peaks 8 micron	Infra Red Adsorption Peaks 21 micron	Photoconductivity Mercury Arc	Photoconductivity Visible Light
A	.021 g.	.81 mm.	0	2	2537 A	3.5	—	120×10^{-9} amps.	4×10^{-9} amps.
B	.026	.41	1	5	2740	27	10.0	35	5
C	.020	.71	1	6	2280	—	10.0	3,500	57,000
D	.024	.71	10	3	2960	1	1	350	3
E	.016	.41	2	6	2537	6	8	250	3
H	.028	.95	0	6	2480	1	3.5	55	1
Q	.019	.45	10	3	2380	—	—	440	4
02	.152	2.60	3	6	2890 2750	3.5	9	59	6
03	.092	2.00	2	2*	2537	1	—	430	10
05	.062	2.00	7	6	2537	—	—	350	7
HC-1	.148	2.00	6	6	2960	1	—	91	4
HC-2	.235	3.9	2	1	3110	—	—	150	10
TSC-2	.034	.80	3	5	2880	11	—	180	5
TSC-4	.043	.85	1	2	2537	4	4.5	200	4
TSC-6	.125	.74	0	6	2300	5	4.5	40	
FSC-2	.034	.48	3	3	2480	7	—	270	5
FSC-8	.045	.45	1	3	2537 2380	21	6	200	22
FSC-10	.043	1.17	0	3	2880 2350	23	5.5	40	2

The gamma counting property is based on comparison with diamond Q. (A correction for size was applied.) A diamond which did not count is indicated by 0, those counting with 1 to 10 percent of Q's efficiency are rated 1, and so on up to 10. The infra red absorption peaks are given in percent absorption. The absorption at 7 microns was used as a reference for the 8 micron peak and the absorption at 18 microns as the reference for the 21 micron peak. Luminescence of the entire diamond is rated 1, partial luminescence 2 to 5, full scale luminescence 6. The (—) indicates the infra red absorption peak is not present.

* Half blue and half yellow luminescence.

photoconductivity of the diamond. The remaining positive charge results in the activated condition for counting nuclear particles. The positive charge will induce a negative surface charge on the electrodes and reduce the potential barrier at the electrode so that electrons may enter the diamond from the negative electrode when a nuclear particle causes ionization. This increases N_0 and hence V eff. In addition, the energy bands will be smoothed out and this will increase the distance δ an electron moves before being trapped and hence increase V eff.

Summary

Crystal conduction counters have the advantages of very fast resolving times, a pulse height which is proportional to the energy of the incident particle, and for gamma rays a high stopping power. The main disadvantage is the accumulation of a space charge field. This disadvantage can be overcome by irradiating a good counting diamond with red light while using it for counting, or by using the diamond in an activated counting condition. Some correlation between gamma counting properties, the eight and twenty-one micron infra red absorption peaks and the photoconductivity of diamond is observed, but several conspicuous exceptions are noted. A tentative explanation of the activated counting condition involves an impurity or defect level about three ev. below the conduction band. Activation of this impurity level is accomplished by gamma counting with the diamond for many hours or irradiation of the gamma counting diamond with light of three to four ev. of energy.

Literature Cited

1. Ahearn, A. J., *Phys. Rev. 73*, 1113 (1948).
2. Blackwell, D. E., Sutherland, G. B. B. M., *J. Ch. Phys., Tome* 46 (1949).
3. Corson, D. R., Wilson, R. R., *Rev. Sci. Instr. 19*, 207 (1948).
4. Friedman, H., Birks, L. S., Gauvin, H. P., *Phys. Rev. 73*, 186 (1948).
5. Hofstadter, R., *Phys. Rev. 72*, 747 (1947).
6. Hofstadter, R., (Private Communication).
7. Kallman, H., On Conductivity in Different Types of Cadmium Sulfide Crystals and on Its Application, Signal Corps Engineering Report E-1036, May 1949.
8. McKay, K. G., *Phys. Rev. 74*, 1606 (1948).
9. Newton, R., *Phys. Rev. 75*, 234 (1949).
10. Ramanathan, K. G., *Proc. Ind. Acad. Sci.*, A, *24*, 130 (1946).
11. Robertson, R., Fox, J. J., Martin, E. E., *Phil. Trans. Roy. Soc.*, A, *232*, 463 (1934).
12. Van Heerden, P. J., The Crystal Counter, Utrecht Dissertation, 1945.
13. Willardson, R. K., Danielson, G. C., *Phys. Rev. 77*, 300 (1950).
14. Woolridge, D. E., Ahearn, A. J., and Burton, J. A., *Phys. Rev. 71*, 913 (1947).

Physics Department
Iowa State College
Ames, Iowa