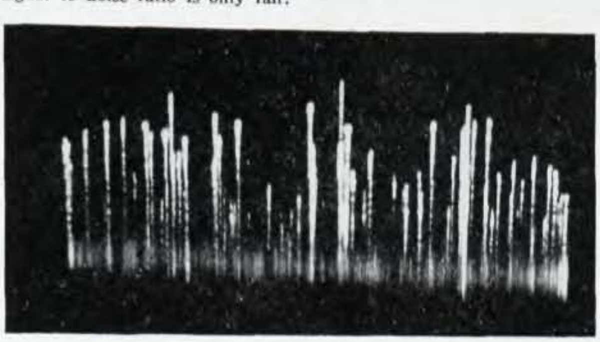
Pulses resulting from the bombardment of a diamond by monoenergetic alpha particles. The pulse height distribution is nonuniform and the signal to noise ratio is only fair.



Development of the crystal counter (essentially an ionization chamber that is solid instead of being filled with gas) has progressed in the last few years, but is still delayed for lack of better understanding of crystals and their electrical behavior.

The Crystal Conduction Counter

By K. G. McKay

WHENEVER A NUCLEAR PHYSICIST observes a new effect caused by an atomic particle, he tries to make a counter out of it. After all, neutrons, protons, and their ilk are elusive little beasties and their detection and measurement form the life blood of experimental nuclear physics. The fact that charged particles can ionize gas molecules has been exploited to produce the ionization chamber, the proportional counter, and the Geiger counter. The fact that certain solids luminesce when bombarded with high-speed particles made possible many of the early studies in nuclear physics where the observer peered at a zinc sulphide screen through a microscope and laboriously counted the minute light flashes caused by alpha particles striking the screen. Recently, a photomultiplier tube has supplanted the eye-weary observer, resulting in the modern scintillation counter which plays an important role in all nuclear physics laboratories today. Thus it is only logical that attempts should be made to utilize the electrical effects produced in solids by ionizing particles—the solid state equivalent of an ionization chamber. Indeed, such effects have been sought for many years, yet it is only since World War II that new theory and new techniques have demonstrated that the crystal counter is actually a potentially useful measuring instrument. That its application is potential is an unfortunate consequence of the complexity of the solid state and the lack of an adequate understanding of the detailed electrical behavior of real crystals.

LET US FIRST CONSIDER just what a crystal counter is. An electric field is applied across a solid; an ionizing particle enters the solid and produces free electrons in the solid; free electrons move through the solid under the influence of the electric field and this charge displacement is measured externally as a more or less instantaneous current. In this idealized form it is indeed nothing more than the familiar ionization chamber with a solid substituted for the gas. At this point it should be emphasized that we are dealing solely with electrical effects; this is in contrast to the scintillation counter which relies for its action on the luminescence produced in a solid by an incident particle.

Now let us consider what solids might be most appropriate. The requirement that we should be able to produce an adequate electric field in the solid limits us to insulators and semiconductors. Next, we would like the incoming particle to produce as large an effect as possible—at least large enough to be measured. Here, however, we are immediately faced with the problem of the actual mechanism involved so we had better stop and take a look at some well established properties of the solid state.

We shall consider insulators first. The electrons in the solid that are of interest to us here are the valence or binding electrons. These are all occupied in the task of binding the atoms tightly to each other. In the ideal insulator there are no free electrons left over and thus, if no extra electrons are injected into the solid, no current can flow when an electric field is applied: i.e., we have an insulator.

This situation is changed when we bombard with an ionizing particle such as an alpha particle. Practically all of the energy of the alphas will be dissipated in collisions with the electrons which bind the atoms together. These collisions knock the erstwhile bonding electrons loose and set them free to roam through the crystal. However, these free electrons are not the only current carriers. Another type of carrier arises because the places where those electrons came from are now empty. In some crystals, like diamond, the electrons in neighboring bonds (positions) can exchange places with each other readily. If an electron in, say, position A, jumps into neighboring position B where a bonding electron is missing, there will no longer be an electron in position A. This is the same as saying that the vacancy has moved from B to A and thus, in this case,

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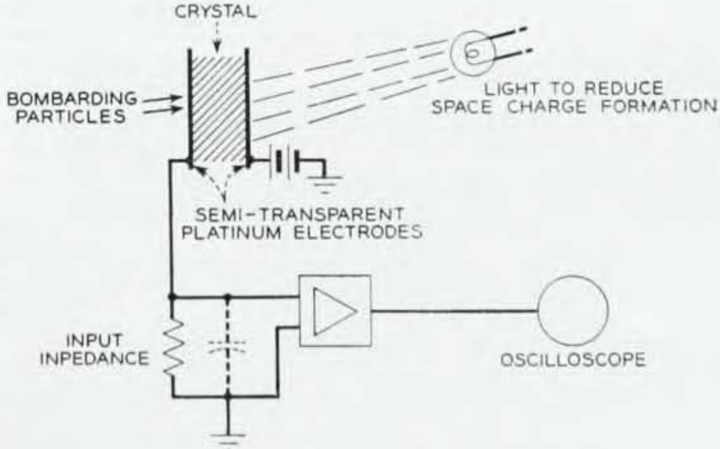
is mobile. Since the vacancy occurs in what is normally a neutral crystal it forms a region of positive charge and the fact that it is mobile permits it to act as a charge carrier in a crystal. Thus each significant collision made by a bombarding particle produces both a free electron and a positive hole. Under the influence of an electric field, the electron moves off in one direction, the positive hole moves off in the other direction, and both contribute to the observed current. We anticipate that a free charge carrier will bounce around in the crystal because of thermal vibrations and will drift in the direction of the applied field with a constant velocity. This drift velocity is equal to the field times a constant which is called the mobility.

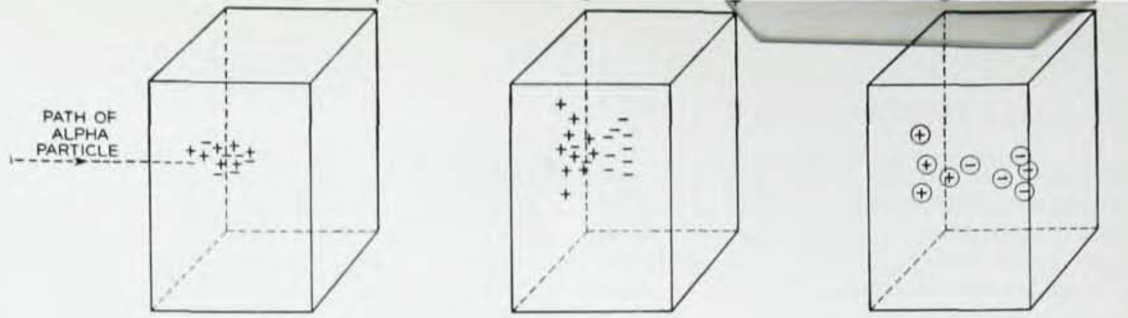
We also realize that in any actual crystal that we might use, there are local imperfections that disrupt the symmetrical arrangement of the atoms. These imperfections might consist of foreign atoms (impurities) or merely misplaced atoms of the crystal. From experience we know that these imperfections may prove very attractive to free carriers; a carrier drifts into the region around an imperfection, exchanges energy with the surrounding atoms and then finds that it doesn't have enough energy to leave the region because of the peculiar local electrical disturbance set up by the imperfection—the carrier has been trapped just as a billiard ball is pocketed. The longer an untrapped carrier remains free in the crystal, the more likely it is that it will drift into such a region and be trapped. At low field strengths, the carriers drift more slowly and take longer to traverse the crystal; trapping becomes more effective and we expect smaller currents. Moreover, the trapped carriers, by virtue of their electrical charge, set up internal electric fields which oppose the applied field and cause the current to diminish with time. This is a nuisance but can be avoided by releasing the trapped charges through the application of heat or of light or through the use of ac fields in which, on alternate half cycles, positive holes are supplied by bombardment which recombine with the trapped electrons and vice versa. All three methods have been successfully used.

All of this suggests that we should minimize the traps with their consequent space charge problems and should use crystals in which the carriers drift very quickly, i.e., have a high mobility. This leads us to study certain single crystals of high crystalline perfection. For example, diamond, zinc sulphide, and several other metal-sulphur compounds have been used successfully at room temperature while silver chloride and similar crystals are effective at liquid nitrogen temperature. However, the behavior usually cannot be explained solely by the basic theory suggested above. If we bombard a crystal with monoenergetic particles, such as alphas from polonium, and with the geometry shown in the figure on this page, we would expect that the resultant conductivity pulses would be uniform in size and the pulse height would be proportional to the energy of the alphas. Actually this is almost never the case; the observed heights scatter very widely. This implies that since the different alphas enter different regions of the crystal, these regions must differ in their electrical properties. For other reasons we believe that the variation occurs in the conducting properties of the crystal and not in the carrier excitation process. The simplest explanation of this effect is to postulate an inhomogeneous distribution of traps so that one alpha particle strikes a relatively trap-free region and the resultant carriers travel a long distance before being trapped, while the next alpha hits a trap-rich region and the carriers are immobilized before they can drift at all. Undoubtedly this is an important factor. However, the results of subsidiary measurements on some crystals indicate that variations in trap density do not tell the full story. It has become evident that even an excellent insulator may possess more or less localized regions of appreciable conductivity in the absence of any bombardment. This means that if we apply a voltage to a crystal before any bombardment has occurred, the electric field may vary greatly within different parts of the crystal. Thus a region that responds exceptionally well to bombardment may be merely one in which the carriers are produced in an exceptionally high local field. Theory shows that the introduction of an extremely small quantity of impurities into a really good insulator should lead to just such a result, and experiments appear to confirm it.

Thus the response of insulators may vary rather extensively with position, because of trap and field inhomogeneities, and also with time, because of space-charge build-up. To this we must add the disconcerting fact that in the crystals studied to date, different crystals of the same species vary enormously in their response one from the other. These are not overwhelming difficulties; there are still many applications for which this form of crystal counter is potentially useful. However, this variable response has reduced the usefulness of insulating crystal counters up to the present.



Typical schematic arrangement for studies of bombardment conductivity in insulating crystals such as diamond.



The simplest case of alpha bombardment conductivity.

SO FAR, we have discussed the simplest type of action in which we measure only the charge carriers that are directly excited by the incoming radiation. The next step is to consider the so-called secondary currents which, under certain circumstances, may be present. These may occur in different ways but can best be explained by considering the following: assume that we have a long pencil-like insulator which is somewhat imperfect. It normally has a few free electrons throughout and thus should be a fair conductor. However, at one point there is a thin barrier region where the composition of the solid differs from that elsewhere. The effect of this electrical barrier is to repel electrons from that region and thus the free electrons cannot readily pass from one end of the crystal to the other even when a sizeable electric field is applied, i.e., outwardly this looks like a good insulator. Now if we bombard in the neighborhood of the barrier, we will produce both free electrons and positive holes. The holes will be attracted to the barrier region and, if enough of them collect there, the region will become more positive and thus will become more attractive to electrons. The free electrons from the neighboring region will move over to the barrier and on to the other side. Thus we now have a relatively free flow of electrons from one side of the crystal to the other, and this will continue until the abnormal concentration of positive holes disappears through recombination with the electrons. The entire action is like that of a dam which normally prevents the flow of water. The positive holes act to lower the height of the dam temporarily, thus allowing a rather large quantity of water to pass. The important point is that the charges excited by the radiation now merely control the movement of free charges which were originally in the solid. There are several consequences of this.

1. Enormous amplification is possible. A million electrons may traverse the crystal for each positive hole produced by the bombardment.

2. The response is relatively slow since the pulse lasts as long as the lifetime of the abnormal hole concentration in the barrier.

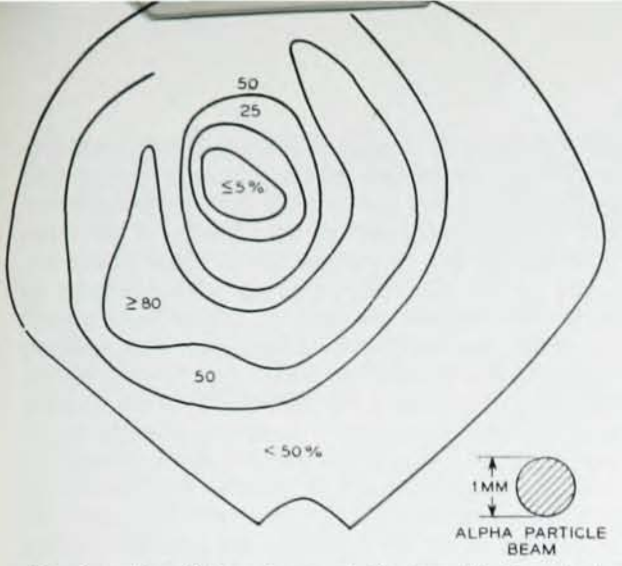
3. The response is highly nonuniform since the total electron flow depends critically on the number of holes in the barrier and this in turn depends on how close to the barrier they were produced.

Different models for secondary current flow could be considered. However, this particular explanation seems to apply in many cases to the behavior in a material such as cadmium sulphide which has been studied extensively as a counter. One important point is that the barrier concept may be applicable to insulators with inhomogeneous electric fields such as those considered earlier. This implies that secondary currents may indeed be present even in excellent insulators like diamond, thus further accentuating the nonuniform response.

It is evident that the biggest single drawback to the use of insulators is the uncertainty concerning the electric field distribution within the solid. This forces us to look into the potentialities of certain semiconductors where the field distribution can be determined. A quick look makes this appear really promising.

A SEMICONDUCTOR is qualitatively like an insulator except that it always has a sufficient number of free charge carriers floating around to make it reasonably conducting. The carriers usually come from impurity atoms that are added—deliberately or unintentionally—and these free carriers may be either electrons or holes. An excellent example to consider is the semiconductor germanium; the widespread interest in its use in transistors has greatly advanced the art of making large single crystals with predetermined distributions of desirable impurities. Here we find that trapping by individual impurities is negligible, and that the normal population of free carriers prevents the cumulative build-up of space charge. As a bonus, the mobilities of free electrons and holes are high. The electric field distribution is usually determined by the distribution of impurities. It can often be measured and does not change subsequently. Thus we have here most of the properties we desired for insulators. The problem is how to obtain an adequate field gradient to ensure that the bombardment-induced conductivity pulse is measurable.

Through the proper distribution of impurities we can make one part of a germanium crystal with electrons as the free carriers (an *n*-type semiconductor) and the rest of it with positive holes as the carriers (a *p*-type semiconductor). The transition region between the two



Plot of counting efficiency in percent of a large flat diamond when bombarded by alpha particles. Such wide variations in sensitivity in different parts of a diamond are usually encountered. *Courtesy Dr. A. J. Ahearn.*

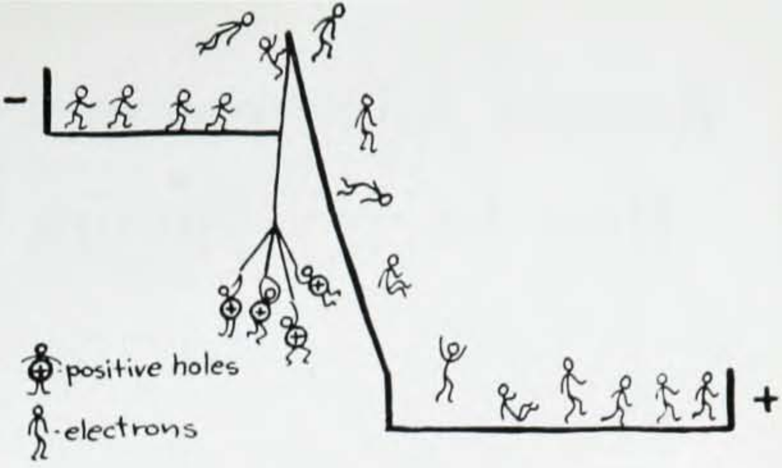


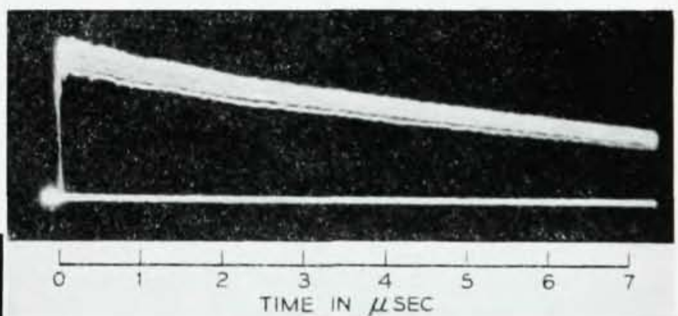
Illustration of secondary currents at an *n-p-n* semiconductor junction or barrier in a poor insulator. Positive holes, produced by bombardment, are trapped in the barrier region making it more positive in potential and thus permitting more electrons to flow across the specimen.

parts is called the *n-p* barrier and acts as a rectifier. If biased in the direction of low current flow, it is somewhat analogous to a thin slice of insulator separating two massive electrodes but with all the desirable properties listed in the previous paragraph. Tests of such junctions by electron or alpha particle bombardment show that they perform as predicted with a response proportional to the energy of the incoming particle and no cumulative space charge effects. The voltage applied to the junction for good counting is no more than about two volts and the pulse height is about ten times that obtained from an air ionization chamber. The catch is that although the barrier may have an area of several square centimeters, its thickness rarely exceeds 10^{-3} cm. This makes a very small sensitive volume and thus qualifies the device in its present form for only a few rather specialized tasks such as coincidence studies with fairly densely ionizing particles where high spatial resolution is required.

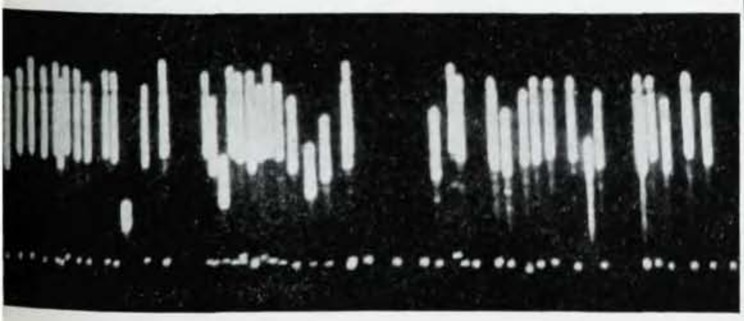
It is still too early to evaluate the potentialities of semiconductor counters. *n-p* junctions can be fabricated in many forms and shapes. *n-p-n* junctions, which are the same as those used in transistors, have been shown to give secondary currents such as described above. The use of silicon in place of germanium has also proved highly satisfactory as a counter of alpha particles. By combining different materials with various structures, a wide variety of counting properties is anticipated.

TO SUM UP, the crystal conduction counter holds the bright promise of being a compact, high-speed counter. It requires but an electrical connection to it rather than the awkward light path linkage of the scintillation counter. It responds to each of the basic nuclear particles if the appropriate shape and composition are used. At present, we still do not know enough about insulators to use them really effectively. Semiconductors come much closer to all of the desired characteristics except for the limitation of the size of the sensitive volume.

These examples merely outline the present status of the crystal counter. The field of solid state physics is actively progressing and we expect eventually to see that progress reflected in solid state devices such as the crystal counter. It may always prove to be a specialized tool but it will nevertheless be a valuable one.



Pulses from 16 alpha particles bombarding germanium *n-p* junction displayed on expanded time scale. Still greater time scale expansion shows pulse rise time to be less than 2×10^{-8} secs and it is probably of the order of 10^{-9} secs.



Pulses resulting from bombardment of germanium *n-p* junction by monoenergetic alpha particles. Pulse height distribution is good and signal to noise ratio is greater than 100.