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# Photoelectromagnetic Effect in Indium Arsenide

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An experimental study of the photoelectromagnetic (PEM) effect in single crystals of *n*-type and *p*-type indium arsenide at room temperature is described. For *n*-type material it is found that the PEM short-circuit current is proportional to the magnetic induction for both high and low surface recombination velocities. In contrast, the PEM short-circuit current for *p*-type material is found to be nonlinear with respect to the magnetic induction; and the degree of nonlinearity depends markedly on the surface recombination velocity. It is shown that these results are consistent with the theoretical relations proposed by Kurnick and Zitter. Values for the bulk lifetime of electrons and holes are calculated using the PEM effect and photoconductivity data and are found to be approximately $6\times10^{-8}$ sec for *n*-type material and $5\times10^{-10}$ sec for *p*-type material. Estimations based on experimental data indicate that the surface recombination velocity for *n*-type material is in the range from 0 to $10^3$ cm/sec for an etched surface and equal to $10^5$ cm/sec for a hand-ground surface. It is shown that large errors can be made in the measured values of the bulk lifetime when the spectral range of the exciting light includes the absorption-edge region.

## I. INTRODUCTION

When light is strongly absorbed on the surface of a semiconductor placed in a magnetic field whose direction is perpendicular to the normal of the illuminated surface, an electric current is generated. This is called the photoelectromagnetic (PEM) or photomagnetoelectric (PME) effect. It results from the fact that the electrons and holes created at the surface by the incident light are deflected in opposite directions by the magnetic field as they diffuse into the body of the semiconductor. The effect was first observed in cuprous oxide.[1] Subsequently, it has been studied in germanium,[2–5] lead sulfide,[5,6] silicon,[4] and indium antimonide.[7]

The magnitude of the PEM current is dependent upon the photon flux, magnetic induction, lifetime and mobilities of the electrons and holes, temperature, and surface recombination velocity. Theoretical expressions relating these quantities have been proposed by several workers. Early theories[3,8] were based on the assumption that under open-circuit conditions the generated current is everywhere zero. Van Roosbroeck[9] has pointed out that this assumption is not tenable and that only the integrated current should be assumed zero. Recently, new theoretical models have been proposed for the case of small Hall angles by van Roosbroeck[9] and for the case including large Hall angles by Kurnick and Zitter.[7]

The present work involves the experimental study of the PEM effect in single crystals of *n*-type and *p*-type indium arsenide at room temperature. Indium arsenide was of particular interest because its large electron mobilities make it possible to obtain large Hall angles at moderate magnetic fields. This afforded an opportunity to check the Kurnick and Zitter large Hall-angle theory which has been verified previously for only *p*-type and intrinsic indium antimonide.[7]

## II. THEORY

The Kurnick and Zitter treatment of the PEM effect applies to the small signal, steady state condition. The relations which are derived pertain to samples whose dimensions are large in comparison to a diffusion length. For the case of extrinsic material the PEM short-circuit current per unit sample width is given in terms of the mks system of units by

$$i_s=\left(1+\frac{1}{b}\right)\frac{eI\mu B\tilde{L}_D}{(1+\tilde{\mu}^2B^2)^{\frac{1}{2}}}\left(\frac{1}{1+(\tau S/\tilde{L}_D)(1+\tilde{\mu}^2B^2)^{\frac{1}{2}}}\right). \quad (1)$$

The symbols used here and in other parts of this paper are defined in Table I. For the case of indium arsenide, the $1/b$ term is small in comparison to 1 and will be ignored. If the surface recombination velocity is large enough so that $\tau S/\tilde{L}_D\gg1$, Eq. (1) becomes

$$i_s=\frac{eI\mu B}{1+\tilde{\mu}^2B^2}\left(\frac{\tilde{D}}{S}\right). \quad (2)$$

If, on the other hand, the surface recombination velocity is such that $(\tau S/\tilde{L}_D)(1+\tilde{\mu}^2B^2)^{\frac{1}{2}}\ll1$, then

$$i_s=eI\mu B\tilde{L}_D/(1+\tilde{\mu}^2B^2)^{\frac{1}{2}}. \quad (3)$$

A value for the bulk lifetime can be determined independently of the photon flux and surface recombination velocity by comparing the photoconductive (PC) and PEM signals obtained from a given

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TABLE I. Symbols.

$i_s$—PEM short-circuit current per unit sample width.
$i_{PC}$—photoconductive short-circuit current per unit sample width.
$b$—ratio of electron to hole mobilities.
$e$—magnitude of charge on an electron.
$I$—photon flux.
$\mu$—mobility of electrons.
$\tilde{\mu}$—mobility of minority carriers.
$\tilde{D}$—diffusion constant for minority carriers.
$\tilde{L}_D$—diffusion length for minority carriers.
$\tau$—bulk lifetime of electrons and holes.
$S$—surface recombination velocity.
$B$—magnetic induction.
$E$—electric field.

sample under the same experimental conditions. The expression given by both van Roosbroeck and Kurnick and Zitter for the case of extrinsic material is

$$\tau=\tilde{D}\left(\frac{i_{\mathrm{PC}}}{E}\right)^2\left(\frac{B}{i_s}\right)^2. \qquad (4)$$

A condition on which the Kurnick and Zitter derivations are based is that

$$\mu BE \ll \tilde{L}_D/(\tilde{\mu}\tau).$$

For the indium arsenide used in this work, the right side of this inequality is in the range from $10^2$ to $10^3$ volts/m. Under the experimental conditions applied here the left side of the inequality is never greater than $10^{-2}$ volt/m. Thus, the above condition is satisfied.

## III. EXPERIMENTAL

### (a) Samples

The samples studied were single crystals of *n*-type and *p*-type indium arsenide prepared by reacting constituents in an evacuated, sealed Vycor or silica container. At room temperature the *n*-type material had an electron Hall mobility of 25 000 cm$^2$/volt-sec and a carrier concentration of approximately $3\times10^{16}$ cm$^{-3}$, and the *p*-type material had a hole Hall mobility of 310 cm$^2$/volt-sec and a carrier concentration of approximately $2\times10^{17}$ cm$^{-3}$. The samples were formed as rectangular parallelepipeds with dimensions of approximately $(1\times0.3\times0.1)$ cm$^3$. The length was made relatively long to reduce the significance of end effects. Wires were attached to the ends using standard solder and a zinc chloride flux. The electrodes were masked to eliminate possible photovoltaic effects and to improve the geometry of the illuminated section. Surfaces having high recombination velocities were produced by hand grinding with S. S. White Abrasive Powder No. 1. Low-recombination-velocity surfaces were obtained by etching with CP–4.[10]

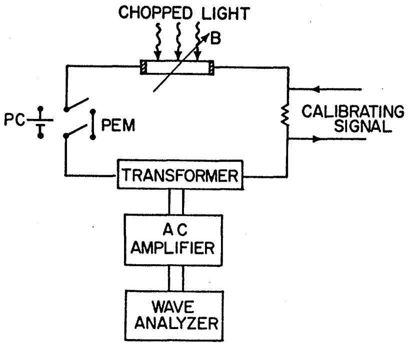

FIG. 1. Schematic diagram of the detecting circuit used to measure photoelectromagnetic and photoconductive signals from indium arsenide.

### (b) Apparatus

The alternating-current, narrow-band detecting circuit shown schematically in Fig. 1 was used to measure the low-level signals associated with the PEM and PC effects in indium arsenide. Light from a 100-watt incandescent projection bulb which was chopped at a frequency of 750 cycles per second was used to illuminate the samples. The resulting ac signal was passed through a magnetically shielded transformer to a battery-operated ac amplifier, after which it was amplified by a narrow-band wave analyzer tuned to the light-chopping frequency. A known signal was injected into the primary circuit to calibrate the system. Signals as small as $10^{-8}$ volt could be measured. The maximum over-all amplification of the circuit was approximately 50 000. The resistances of the samples were in all cases much less than the impedance of the primary of the transformer. Therefore, the measured signals were essentially open-circuit voltages. Values for the short-circuit currents were obtained by dividing the open-circuit voltages by the resistance of the illuminated portion of the sample.

## IV. RESULTS AND DISCUSSION

### (a) *n*-Type Indium Arsenide

The dependence of the PEM short-circuit current on the magnetic induction and surface recombination velocity for *n*-type indium arsenide at room temperature is shown in Fig. 2. The data indicate that $i_s$ is proportional to $B$ throughout the range of magnetic fields studied and for both surface conditions. It can be seen that the magnitude of $i_s$ is strongly dependent upon $S$, the etched sample giving signals more than ten times larger than the hand-ground sample. These results are consistent with Eq. (1). For the *n*-type material used here, $\tilde{\mu}$ is believed to be roughly $10^{-2}$ times the mobility of the majority carrier. Thus, the largest value of $\tilde{\mu}B$ encountered is in the neighborhood of 0.03 and the nonlinear terms appearing in the denominator of Eq. (1) would not be expected to manifest themselves.

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[10] The CP–4 etch was composed of 15 cc CH$_3$COOH, 25 cc HNO$_3$, 15 cc 48% HF, and 0.3 cc Br.

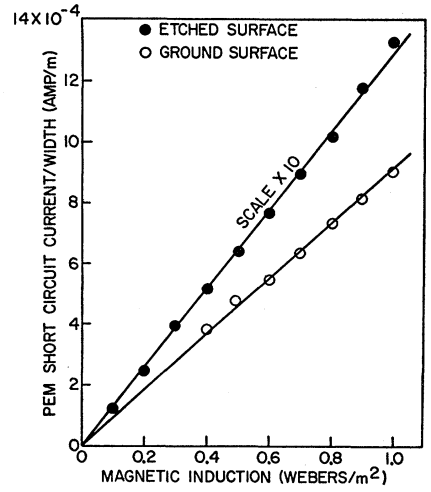

FIG. 2. The dependence of the photoelectromagnetic signal on magnetic induction for *n*-type indium arsenide at room temperature.

Magnetoresistance is a possible complicating factor in the interpretation of PEM data.[9] The resistivity of the samples used in these measurements was found to change less than 10% at the maximum value of the magnetic induction. Such a small magnetoresistance effect was not expected to alter the results significantly. For this reason, no effort was made to correct the data accordingly.

### (b) *p*-Type Indium Arsenide

Data pertaining to the PEM effect in *p*-type indium arsenide at room temperature are given in Fig. 3. These data contrast sharply with those applying to the *n*-type material. In this case both of the curves are nonlinear and the degree of nonlinearity depends markedly upon the surface condition of the sample. The curve for the etched sample appears to be leveling off as $B$ is increased whereas the one for the hand-ground sample passes through a maximum. The magnitude of the PEM current is strongly dependent upon the surface recombination velocity as was found for the case of *n*-type material. These results are also consistent with Eq. (1). The minority-carrier mobility for this *p*-type material is expected to be large enough so that the nonlinear terms of the equation will become significant at moderate values of the magnetic induction. The agreement between the experimental data for the two surface conditions and the two limiting theoretical relations given by Eqs. (2) and (3) can be studied conveniently by plotting the data as shown in Figs. 4 and 5. The linearity of the data in either case is a measure of the fit between the experimental data and the corresponding theoretical relation. It can be seen from Fig. 4 that the data pertaining to the ground sample are in good agreement with Eq. (2) which describes the PEM effect in the limiting case of high surface-recombination velocity. Similarly, it can be seen from Fig. 5 that the behavior of the etched sample is well described in terms of Eq. (3) which applies to the limiting case of low surface-recombination velocity.

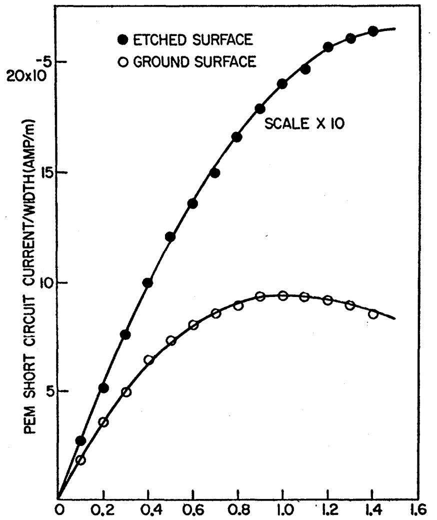

FIG. 3. The dependence of the photoelectromagnetic signal on magnetic induction for *p*-type indium arsenide at room temperature.

A value for the minority-carrier mobility can be obtained easily from the data as plotted in Figs. 4 and 5. In both cases $\tilde{\mu}^2$ is given by the ratio of the slope to the intercept of the straight line. In this way, a value of 11 000 $\mathrm{cm}^2$/volt-sec was obtained for the minority-carrier mobility from both graphs. Considering the large differences in the nature of the experimental results associated with these sets of data, this agreement in the calculated value of $\tilde{\mu}$ can be considered support for the theoretical model. This value of the minority mobility when compared with the majority mobility estimated from Hall data yields a value of $b$ of 35. The magnitude of the electron mobility determined in this way is in reasonable agreement with Hall data pertaining to *n*-type indium arsenide. It has been found in this laboratory that the electron Hall mobilities of *n*-type material having carrier concentrations approximating that of the *p*-type sample used here fall in the range from 10 000 to 19 000 $\mathrm{cm}^2$/volt-sec.

### (c) Bulk Lifetime and Surface Recombination Velocity

The determination of the bulk lifetime of the electrons and holes on the basis of the PEM effect alone requires a knowledge of the photon flux and the surface recombination velocity, both of which are sometimes difficult to determine accurately. The value of $\tau$ can, however, be determined independently of these quantities by measuring both the PEM and PC short-circuit currents for a given sample under identical experimental conditions. The simplification results from the fact that the magnitudes of both the PEM and PC short-circuit currents depend in the same way upon the photon flux and surface recombination velocity but in different ways upon the bulk lifetimes. The resulting simple relation is given by Eq. (4). This is sometimes referred to as the PC–PEM ratio method of determining $\tau$. It is based on the assumption that the lifetimes associated with the PEM and PC effects are equal.

Applied to the $n$-type material used here, the PC–PEM ratio method yielded bulk-lifetime values of $6.5\times10^{-8}$ sec for the case of the hand-ground sample and $5.8\times10^{-8}$ sec for the etched sample. These two values can be considered equal, since their difference is within the range of uncertainty in the experimental method. The equality of these values of $\tau$ obtained from samples having different surface conditions is substantiating evidence for the general validity of the ratio method. The evaluation of $\tau$ by the ratio method required a knowledge of the minority-carrier mobility. It has been assumed for this $n$-type material that the minority-carrier mobility at room temperature is approximately $10^{-2}$ times the majority-carrier mobility determined from Hall measurements.

Values of the surface recombination velocity for $n$-type material can be approximated on the basis of the value of $\tau$ given above and the ratio of the PEM short-circuit currents of the ground and etched samples taken from the data of Fig. 2. Such a calculation indicates that the value of $S$ is in the range from 0 to $10^3$ cm/sec for the etched sample and is approximately $10^5$ cm/sec for the hand-ground sample. In this calculation it is assumed that the behavior of the etched sample is described by Eq. (3). This has been shown to be the case for $p$-type material in Sec. IV(b).

A value for the bulk lifetime of the carriers in $p$-type material could not be determined using the PC–PEM ratio method because the level of the photoconductive signal was too low for accurate measurement. However, the approximate value of $5\times10^{-10}$ sec was obtained for $\tau$ in etched $p$-type material by comparing the magnitude of its PEM short-circuit current with that of the etched $n$-type material for which $\tau$ is known.

### (d) Consistency Tests

The values of $\tau$ determined under varying experimental conditions by the PC–PEM ratio method serve as a basis for consistency tests pertaining to three of the assumptions on which the theory and experimental method are based, as described below.

(1) It is assumed in deriving Eq. (4) that the small-signal condition is satisfied. Van Roosbroeck[9] has shown that the value of $\tau$ measured by the ratio method is independent of photon flux for small signals but becomes dependent upon the photon flux when the small-signal condition is no longer satisfied. To be consistent with the theory used here, the measured value of $\tau$ must be independent of $I$.

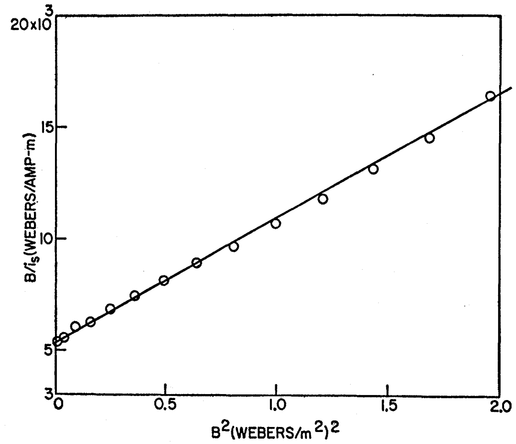

FIG. 4. Photoelectromagnetic data obtained from $p$-type indium arsenide with a ground surface. The linearity of the data plotted in this way is a measure of the fit between the experimental data and the theoretical relation given by Eq. (2) for the limiting case of high surface-recombination velocities.

(2) It is assumed in applying the ac method of detection that measured values of the signal amplitude are not distorted by transients. Bulliard[4] has shown that the transients associated with the PC and PEM signals are different functions of time. Consequently, if transients do contribute significantly to the pulses, the values of $\tau$ measured by the ratio method would be expected to show a frequency dependence. A necessary condition for the use of an ac detecting system for these measurements is that the measured value of $\tau$ be independent of the light-chopping frequency.

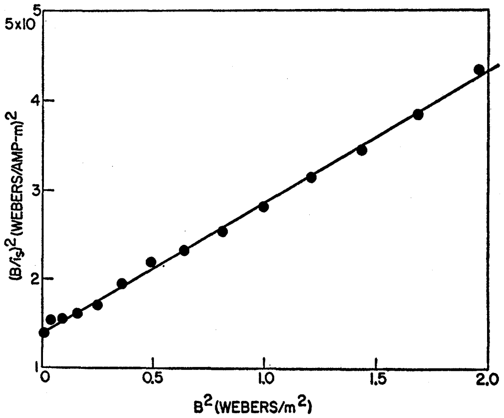

FIG. 5. Photoelectromagnetic data obtained from $p$-type indium arsenide with an etched surface. The linearity of the data plotted in this way is a measure of the fit between the experimental data and the theoretical relation given by Eq. (3) for the limiting case of low surface-recombination velocities.

(3) It is assumed in the theory used here that all the incident photons are absorbed at the surface of the semiconductor. It is expected that the measured value of $\tau$ will depend upon the absorption constant of the

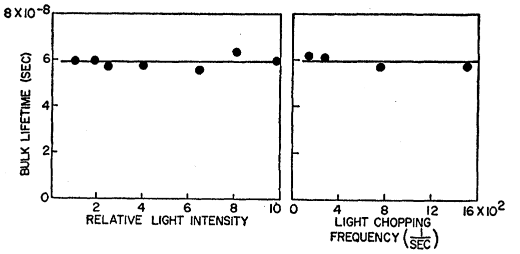

FIG. 6. Bulk lifetimes of electrons and holes in etched *n*-type indium arsenide at room temperature measured by the PC–PEM ratio method under various experimental conditions.

light in a spectral region where this boundary condition is not satisfied. This follows from the fact that the PEM signal depends strongly upon the density gradient of the electrons and holes whereas the PC signal depends on their integrated populations. Thus, to be consistent with the assumed boundary condition, values of $\tau$ measured by the ratio method must be independent of the absorption constant of the exciting light.

Figure 6 presents results of consistency tests (1) and (2) applied to etched *n*-type material. It can be seen that $\tau$ is independent of the chopping frequency and light intensity. These results are consistent with the corresponding assumptions discussed above.

Figure 7 illustrates the significance of the boundary condition on the measured value of $\tau$. In this figure the length of each horizontal line indicates the width of the spectral region of the exciting light used in the determination of the corresponding $\tau$. Light which includes wavelengths in the neighborhood of the absorption edge where the absorption constant changes rapidly and where the boundary condition is not expected to be satisfied leads to values of $\tau$ which are larger than those associated with light of shorter wavelengths. Thus, to be consistent with the assumed boundary condition, the long-wavelength light must not be used. The data indicate that large errors can be made in the value of $\tau$ measured by the PC–PEM ratio method when the spectral range of the exciting light includes the absorption-edge region.

It has been found that many samples of indium arsenide fail these consistency tests even though the experimental conditions and the characteristics of the material are such that the assumptions described above should be satisfied. These irregularities have not been studied systematically. It is possible that they are related to inhomogeneity of the material. The consistency tests were of particular value in this work as a means of identifying and rejecting such irregular samples.

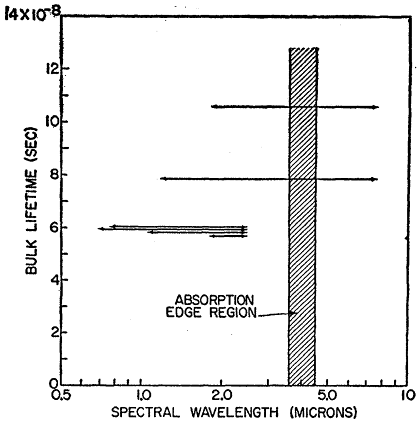

FIG. 7. The dependence of the measured value of the bulk lifetime of the electrons and holes in etched *n*-type indium arsenide on the spectral composition of the exciting light. The length of each horizontal line indicates the width of the spectral region of the exciting light used in the determination of the corresponding bulk lifetime.

## V. SUMMARY

The experimental results pertaining to the dependence of the PEM short-circuit current on the magnetic induction are consistent with the theoretical model proposed by Kurnick and Zitter. The value of the bulk lifetime of the electrons and holes determined by the PC–PEM ratio method was found to be independent of the surface recombination velocity, and the intensity and chopping frequency of the exciting light. These are necessary requirements for the application of the theory and method used here. Finally, the strong sensitivity of the measured value of the bulk lifetime to the spectral composition of the exciting light in the neighborhood of the absorption edge has been demonstrated.

## VI. ACKNOWLEDGMENTS

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