Gigahertz Radiation from Magnetic-Field-Free Electron-Hole Plasmas

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This work shows that gigahertz radiation is emitted from electron-hole plasmas in p-InSb at 77°K whose only external influence is an applied voltage. In order to satisfy the conditions for radiation, the plasma must have a conductance which falls within a limited range. The appropriate plasma conductances require unusually high average electric field strengths E with attendant low average current densities J near threshold, or large J above threshold. The area of the J-E plane associated with radiation is accessible only with plasmas produced in high-quality InSb. More conductance conditions necessary for radiation become accessible by applying a staircase voltage function instead of the usual square wave, because plasma is accumulated from step to step. Some properties of the radiation are described, such as its extreme sensitivity to plasma conductance, its decay characteristics, and a possible correlation between radiation amplitude and current level. The radiation observed at current levels which are far above its current threshold occurs during plasma pinching with two orders of magnitude more plasma current flowing than flows near threshold, namely ~2 A instead of ~20 mA. A further extension of accessible conductance conditions that are suitable for producing radiation, particularly an extension to higher electric field strengths at low current densities, is obtained by application of magnetic field strengths of a few hundred gauss. Many data obtained by fulfilling the necessary condition for radiation, namely, the appropriate range of plasma conductance, are summarized. Evidence that this is not a sufficient condition when the plasma conductance is "tuned" by means of a magnetic field is discussed.

I. INTRODUCTION

THE occurrence of gigahertz radiation emanating from injected plasmas in p-InSb at 77°K, whose only external influence is an applied voltage, has been reported briefly.[1] These observations were made by adjusting the plasma conductance in an unusual way: The driving voltage for producing and maintaining the plasma was applied in the form of successively decreasing steps resulting in plasma accumulation in the later steps, as described in Sec. II. A full report of these results is contained in Sec. III. It has also proved possible to produce the radiation during the application of a simple square wave pulse, and these data are also included in Sec. III.

A theory explaining this effect is not complete; however, a collision-induced instability has been predicted by Drummond, Nelson, and Hirshfield[2] for a plasma with a δ-function velocity distribution that is subject to isotropic scattering. This theory has led Nelson[3] to look for a similar longitudinal instability at frequencies much less than the plasma frequency in an electron-hole plasma, since the optical phonon excitation rate in InSb varies strongly with electron velocity, and the essentially speed-conserving electron-impurity collisions tend to make the electron velocity distribution isotropic. The initially isotropic velocity distribution is raised in energy by the electric field until the power input is balanced by excitation of optical phonons. This model leads to a stationary velocity distribution which, in the limit of small plasma density, has a population inversion. The resulting dispersion relation under the assumption of constant mean free time between collisions shows a growing mode. The preliminary results[3] of this theory agree well with the experimentally observed approximate threshold conditions (Fig. 4). The theory will be reported later.

The plasma conductance can also be adjusted by the application of small magnetic fields. The effect of a magnetic field in general is to *reduce* the plasma density at some given electric field strength E, whereas the staircase voltage input mentioned in the first paragraph tends to *increase* the density at a given E, compared with the density obtained by simple plasma injection. The reduction in plasma density occurs because a magnetic field pushes both the electrons and holes toward a surface, thus enhancing recombination. This "pushing" is accomplished by the helical instability and the Hall effect whenever components of magnetic field parallel and perpendicular, respectively, to the direction of current flow are present. A combination of the two methods of varying plasma conductance, namely a staircase applied voltage and a small magnetic field, has produced a wide range of conditions under which emission is observed, as reported in Sec. III.

In Sec. IV the properties of the radiation and the conditions for producing it are summarized. These are contrasted with those pertaining to a type of radiation previously observed to emanate from electron-hole plasmas which must be subjected to large magnetic fields, an effect discovered by Larrabee and Hicinbothem.[4]

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[1] B. Ancker-Johnson, Bull. Am. Phys. Soc. **12**, 772 (1967); Appl. Phys. Letters **10**, 279 (1967). See also D. K. Ferry, R. W. Young, and A. A. Dougal, Z. Naturforsch. **22a**, 576 (1967).

[2] J. E. Drummond, D. J. Nelson, and J. L. Hirshfield, in *Proceedings Sixth International Conference on Ionization Phenomena in Gases*, (S.E.R.M.A., Paris, 1963), Vol. 3, p. 23.

[3] D. J. Nelson, Bull. Am. Phys. Soc. **12**, 772 (1967).

[4] R. D. Larrabee and W. A. Hicinbothem, Jr., *Symposium on Plasma Effects in Solids* (Academic Press Inc., New York, 1964), p. 181.

TABLE I. Properties of the samples at 77°K.

Sample No.	Resistance (kΩ)	Dimension (mm)	Conductivity (mho/cm)
H110-1	4.5	0.13×0.45×5.1	0.186
H110-4J	3.0	0.50×0.50×4.9	0.67

II. DESCRIPTION OF THE MEASUREMENTS

The experimental arrangement consists of two interdependent circuits, one in which the plasma is produced and the other in which the radiation is detected. A block diagram is shown in Fig. 1. The plasma circuit consists of a charge line (50-Ω coaxial cable) pulser, operated at 30 Hz, in series with a current-limiting resistor, the sample, and a 1-Ω resistor which provides a means of measuring the current. The average electric field strength in the sample is determined by measuring the voltage drop across the sample plus the 1-Ω resistor, since the error introduced by the resistor lies within the accuracy of the oscilloscope measurements. The ten times attenuated (for isolation) voltage drop across the sample, as well as the signal proportional to the current, is monitored by a sampling oscilloscope.

A sample, whose radiation is to be observed, is placed across the shortest dimension of a waveguide, here X-band (8–12 GHz), in a symmetrical position. The waveguide is shorted approximately 2 guide wavelengths from the sample. The radiation is amplified by a traveling wave tube with a maximum gain of ~65 dB and a noise figure of ~8 dB in the frequency range between waveguide cutoff, 6.55 GHz, and the upper limit of the amplifier, ~15 GHz. This signal, after rectification by a broadband crystal detector, is subjected to broadband, low gain (~400×) amplification and then is sampled. The rise and fall times of the detection system are <10 nsec. The detection system begins to saturate when the signal is ~20 dB above the noise level of the entire detection system. The data are collected either by photographing the oscilloscope traces or by plotting the sampled signals on an x-y recorder.

Two samples cut from p-type single crystals were investigated in detail. The equilibrium properties of these at 77°K are given in Table I. Sample H110-1 has an unusually low conductivity; no other sample, even from the same boule, has been found which is as good. Sample H110-4J is typical of the boule. Hall measurements were not made on these samples (to avoid introducing impurities by solder contacts or crystal damage by pressure contacts) but on ones adjacent in the boule, and these yielded hole mobilities between 7.8 and 10×10^3 cm²/V sec. The hole mobility of H110-4J is presumably in this range and the hole mobility of H110-1 is probably higher. Both samples are oriented so that their longest dimensions are parallel to the [110] direction, and their surfaces, which are perpendicular to the direction of the radiation propagation, lie in the (110) plane. The 0.45×5.1 mm² surface of H110-1 is coincident with the (110) plane. The surfaces were prepared by polishing with aluminum oxide (grit No. 600) and subsequently etching in dilute CP4.

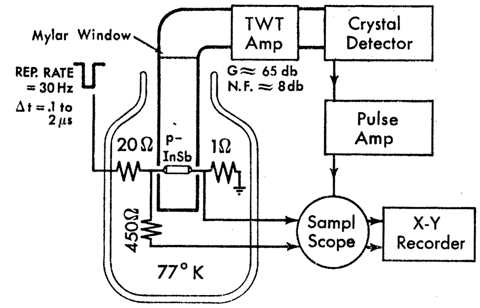

FIG. 1. Block diagram of the experimental arrangement. The holes in the waveguide through which the sample is mounted admit liquid nitrogen below the Mylar window.

Plasma is injected in the usual fashion[5] by using contacts soldered with In on H110-1, which produce relatively low-density plasmas, and with 99% In, 1% Te (biased negatively) and 80% In, 20% (biased positively) on H110-4J, which tend to inject plasmas more readily. The plasma circuit shown in Fig. 1 is mismatched, so reflected pulses occur and produce an

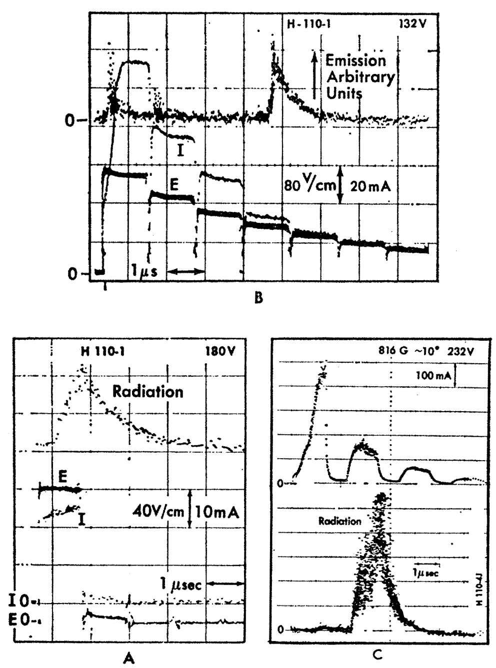

FIG. 2. Oscilloscope traces showing emission under various plasma conductance conditions: (A) Radiation produced by a square wave applied voltage; (B) radiation produced by a staircase applied voltage; (C) radiation in the presence of a magnetic field with the applied voltage in the form of a spaced staircase.

[5] B. Ancker-Johnson, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic Press Inc., New York, 1966, Vol. 1, pp. 379–481); see also in IEEE Region Six Conference Record (IEEE, New York), Vol. 1, 1966, pp. 43–59.

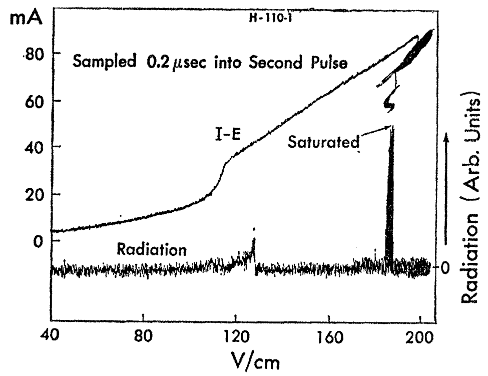

FIG. 3. Conductance and radiation as observed 0.2 μsec into the second pulse.

effective applied voltage waveform that is in the form of successively descending steps, and hence the average field strength and current are also staircase functions,[6] Fig. 2(A). The first current pulse has a shape typical for plasma injection: The current rises in a time dictated by the rise time of the pulser (1 nsec in these experiments) to the magnitude determined by the applied voltage and the equilibrium properties of the sample (Table I), and then rises more slowly to the steady-state magnitude as plasma fills the sample. The density of the injected plasma depends on the electric field strength E as well as on the nature of the contacts.[5] The first reflected pulse, which appears to arrive immediately (on the time scale of the oscillogram) after the applied pulse ends because the mismatch is near the sample, produces a current amplitude which is greater for the E then developed than is the amplitude obtained during the initial pulse at this E. This current increment and hence plasma accumulation occurs because the plasma lifetime in the density range of interest in the present work is 0.9 μsec,[7] much longer than the "off" time between the voltage steps. By this mismatching of the plasma circuit, a variety of conductance conditions are obtained as a function of time which are not obtainable by application of a simple square wave voltage.

The plasma circuit of Fig. 1 can be matched at any applied voltage, for example by placing an appropriate resistance to ground ahead of the 20-Ω resistor. Radiation has also been observed using a matched plasma circuit, as will be shown, although the proper conditions are hard to find, since the available conductances are then severely limited. Comparison of previously obtained conductance characteristics[5,8] with those produced by the present samples (see Fig. 2 of Ref. 1 and the present Fig. 5) immediately suggests that the observations to be reported in the following could not have been made using the quality of InSb previously available.[9]

Care must be taken to distinguish plasma radiation from simple harmonic generation which is observed with the relatively sensitive detection circuit of Fig. 1 when the fast rising, short duration pulses attain sufficient amplitudes across the resistance in the waveguide. The amplitudes are sufficient for observing the harmonics in these experiments only during the first pulse. The distinction between radiation from the plasma and harmonic generation can be made by noting that plasma emission starts after the pulse is on for tenths of a μsec, whereas harmonics are generated while the pulse is turned on, as observed with the same detection system.

In order to study the effect of applied magnetic fields on the radiation, the Dewar in Fig. 1 and its contents are located in a rotatable magnet with its axis of rotation coincident with the radiation propagation direction. A voltage signal proportional to the magnitude of the field, as well as one sensing its direction relative to the direction of current flow in the sample, is available to drive the abscissa of the x-y plotter.

III. RESULTS

Typical results of applying a simple square-wave voltage of the appropriate magnitude to produce gigahertz radiation are illustrated in Fig. 2(A). The peak emission intensity in this case is more than 15 dB above the noise level and it occurs for $I=24$ mA and $E=138$ V/cm. This conductance condition corresponds to an average plasma current density of 13 A/cm^2 and an average plasma density of only $\sim 1\times 10^{12}$ cm^{-3}. The emission starts at a quite precisely defined conductance condition as the I is observed to increase in time (because of plasma injection) in Fig. 2(A). It is typical of all the data that slight changes in the conductance markedly affect the radiation. For example, whether or not radiation occurs can depend on a change in total current flow of 1 or 2 mA, which corresponds to a change in average plasma density of only $\sim 2\times 10^{11}$ cm^{-3}.

The emission recorded in Fig. 2(A) is clearly not related to harmonic generation since the gigahertz signal is first observed 0.3 to 0.4 μsec after the fast rising pulse is on.

Many more conductance conditions suitable for causing the plasma to radiate are obtainable when "left-over" plasma is used to increase the current at a given field strength than can be found when the plasma is acquired simply by injection. Hence, radiation is more readily observed during the application of a staircase

[6] In principle, such a staircase voltage function could be produced by applying consecutive pulses of adjustable amplitude in preference to reflecting one pulse, but in practice it is extremely difficult to obtain sufficiently short delays between sufficiently high voltage pulses, so the latter technique is far more convenient.

[7] B. Ancker-Johnson and M. F. Berg, in *Proceedings Seventh International Conference on Physics of Semiconductors, Paris*, 1964 (Dunod Cie., Paris, 1964), p. 513.

[8] B. Ancker-Johnson, in *Proceedings International Conference on Physics of Semiconductors, Exeter* (The Institute of Physics and The Physical Society, London, 1962), p. 141.

[9] All the InSb used in this laboratory has been purchased from Cominco.

waveform than a square waveform. Figure 2(B) is an oscillogram of the current, average field strength, and radiation produced by such a staircase waveform. Strong emission is recorded during the fourth step. By adjusting the charge line voltage radiation may be observed during any of the first six steps.

The radiation decays more slowly than it builds up as the oscilloscope traces in Figs. 2(A) and 2(B) both show. These times are indicative of events in the plasma and are not limited by the response time of the detection system, as pointed out in Sec. II.

The pulse-reflection technique is particularly successful in observing the radiation near its threshold, i.e., the lowest suitable current and electric field magnitudes. An ascending staircase waveform might be useful in searching for the radiation threshold in the range of low currents and high electric fields, but producing such a waveform is not convenient.[6] Investigating the higher E range is much more easily accomplished by applying modest magnetic field strengths. Field strengths of <100 G, coupled with either the square or staircase waveforms, particularly the latter, produce many more discrete I-E conditions that yield radiation.

Increasing the amplitude of B invariably produces radiation during some step in the staircase if B and the applied voltage are varied through large ranges, e.g., $B\leq 5$ kG, $V\leq 400$ V. (At the high end of these parameter ranges radiation of the kind described in Ref. 4 is also always produced during the first pulse; at such high V the E in the first pulse is sufficient to form an impact-ionized plasma.) Such radiation is not hard to find: During one day 14 samples were tested and all found to radiate during reflected pulses. These samples came from three different boules; some have contacts which inject plasmas copiously, others only niggardly; their cross-sectional areas range from squares as large as 1×1 mm^2 to slabs as thin as 0.09×0.5 mm^2.

An example of radiation observed while the plasma is immersed in a magnetic field is reproduced in Fig. 2(C); in this case $|B|=816$ G and its orientation is slightly away from parallel alignment between E and B. This particular oscillogram is shown to illustrate a strange property of the radiation. The radiation continues to build up in amplitude while the plasma is decaying. Indeed, radiation is still observed after the applied power is off for a sufficiently long time so that nearly all of the injected and accumulated plasma has decayed. A convenient method for observing this effect is illustrated in Fig. 2(c): The staircase waveform is altered by introducing a delay, ~ 1 μsec, between steps which is nearly equal to the lifetime[7] of the plasma.

Another remarkable property of the radiation is shown in Fig. 3, which is an x-y recording of the current and radiation as a function of electric field strength as sampled 0.2 μsec into the second step of a staircase waveform while the charge line voltage was continuously increased. Two conductance ranges are thus generated suitable for producing emsission. The plasma

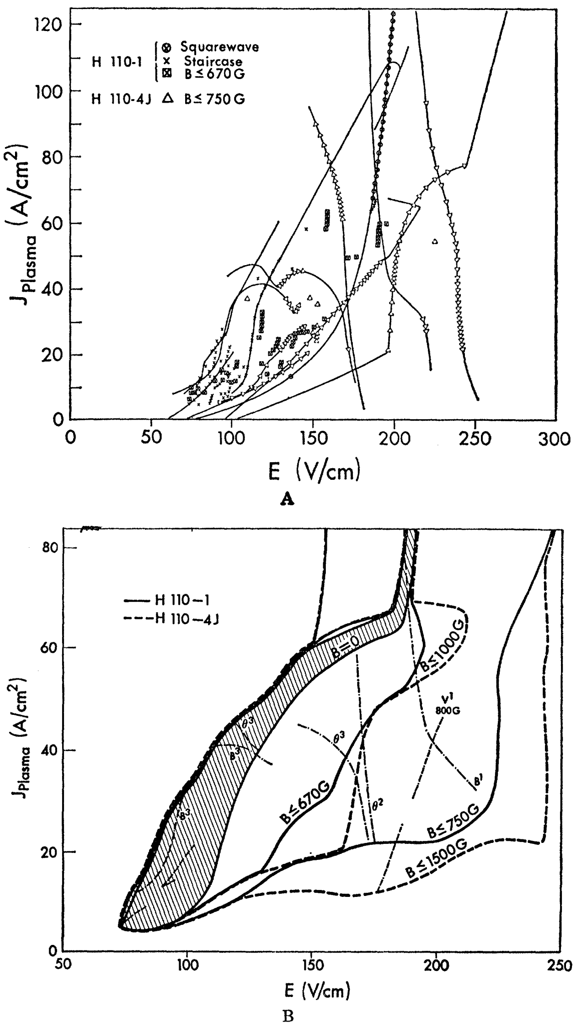

FIG. 4. The average plasma current density as a function of average electric field strength under different magnitudes of applied magnetic field strength between zero and 1.5 kG. (A) The x's and triangles refer to conditions during which sample H110-1 and H110-4J, respectively, radiated. The relative density of the symbols along the J-E curves gives an indication of the intensity of radiation. The lines refer to observed J_{plasma}-E conditions which did not yield detectable radiation. (B) A summary and extension of (a). Enclosed are the parts of the J_{plasma}-E plane which produce radiation when various amplitudes of magnetic field strengths including $B=0$ (shaded area) are applied. The light lines within those areas denote attained J-E conditions which did not produce radiation. Of these the dashed line (near threshold) refers to $B=0$. The identifications associated with the J-E characteristics recorded with dot-dash lines tell which parameter was varied and in which voltage step the observation was made, e.g., B^3 means the magnetic field was varied while events in the third step were observed.

radiates when subjected to the higher field range (185–188 V/cm) only when the lower of the two obtainable current levels occurs. The current decreases discontinuously at $\sim$188 V/cm, and during this lower current condition the emission is strong. The shape of the I-E curve in the range corresponding to intense emission suggests that a correlation exists between the radiation and the plasma density. Whether the current

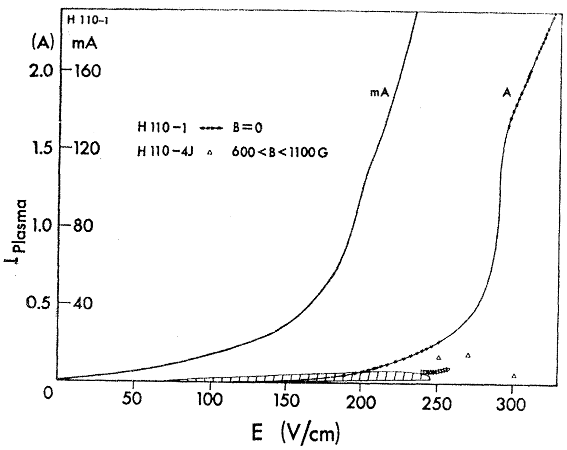

FIG. 5. Plasma current as a function of average electric field strength. This I_{plasma}-E curve is obtained when a square-wave voltage is applied to sample H110-1. The x's show the conditions yielding radiation and their density indicates the relative intensity. The shaded area includes all the data plotted in Fig. 4 for $0 \leq B \leq 1.5$ kG, and the triangles show conditions for emission from sample H110-4J during application of a square-wave voltage.

level drops because the emission builds up, or whether the emission becomes strong because the plasma circuit causes the current to drop at some E cannot be tested by these experiments. However, an I-E curve with such a discontinuous change in I has never been observed in the absence of copious emission, and there is no reason why the simple plasma circuit (Sec. II) should sometimes produce such a strange I-E characteristic. It seems likely, therefore, that the instability responsible for the radiation affects the current magnitude.

The data corresponding to the radiation threshold are summarized in Fig. 4 and the data for radiation corresponding to a much larger plasma conductance range in Fig. 5. The lines in Fig. 4(a) correspond to plasma conductances generated by continuously varying the applied pulse height. Those conditions which produced radiation are denoted by symbols. The density of symbols along a line gives an indication of the radiation intensity. The symbols not associated with lines were obtained from oscillograms. Only one line in the J-E plane can be generated with a given sample[10] when a simple square wave is applied. Sample H110-1 produces emission during part of its J-E curve as indicated by the circled x's. The plain x's show the many more conductances producing emission when the staircase voltage waveform is used, which, as stated above, is a particularly useful technique for investigating the low-J and small-E part of the plane.

Figure 4(A) also summarizes some of the radiation conductances obtained with the application of modest magnetic fields while the samples were subjected to staircase voltage waveforms. The predominant usefulness of an applied B in these experiments in contrast to others[11–20] on gigahertz radiation from InSb is to aid in conductance tuning. Although only one sample was found which possesses the suitable conductance conditions for radiation in the absence of plasma conductance tuning by means of a magnetic field, many radiated when this technique was used. Results reported in this paper are confined to the two samples of Table I and to orientations of B within 15° of parallel to the current flow, in order to make evaluating J_{plasma} easier (avoidance of significant magnetoresistance effects). The use of magnetic field strengths up to 750 G, Fig. 4(a), reveal J-E conditions producing radiation at the high-E part of the J-E plane.

Figure 4(B) is shown to clarify the role of B. The smallest area shaded in the J-E plane enclosed by a solid line demarcates the conductance conditions producing radiation in the absence of a magnetic field. This area is enlarged for the same sample to include larger E when a magnetic field magnitude up to 670 G is applied. When the magnitude is increased to 750 G, more area is enclosed both at higher E, and lower E for $J \geq 60$ A/cm^2. The heavy dashed lines refer to the other sample. The smaller area so enclosed shows the conductances for which emission is observed when $B \leq 1$ kG, and the larger when $B \leq 1.5$ kG.

The data collected in Fig. 4(B) were obtained by three means: (a) the amplitude and angle θ (to within 15° of parallel to current flow) of the magnetic field were held fixed and the charge line voltage V increased; (b) the magnitude of the magnetic field was increased while V and θ were held constant; and (c) θ was varied within 30° around parallel alignment while V and $|B|$ were held constant. Conductances generated by any of these means which did not produce radiation even though the conductances fell in the range that usually did are denoted by the light dot-dash lines in Fig. 4(B). These exceptions show that the state of the plasma necessary for producing radiation in the presence of a magnetic field is not specified by J and E alone.

Plasmas were produced with the J-E conditions for $B=0$ shown by the light dashed lines in Fig. 4 which did not yield radiation even though many other plasmas produced under similar conditions with conductances in those ranges did. It is, however, inherent in the nature of an instability that near its threshold very slight changes in the experimental conditions can make the

[10] Various injection contacts could be affixed to try to produce different conductance curves, but changing contacts is apt to damage the sample.

[11] K. Suzuki, Japan, J. Appl. Phys. 4, 42 (1965).
[12] T. Suzuki, Japan, J. Appl. Phys. 4, 700 (1965).
[13] L. Auchterlonie, Electron. Letters 1, 262 (1965).
[14] M. Toda, Japan, J. Appl. Phys. 4, 854 (1965).
[15] H. Morisaki and Y. Inuishi Japan J. Appl. Phys. 5, 343 (1966).
[16] S. J. Buchsbaum, A. G. Chynoweth, and W. L. Feldmann, Appl. Phys. Letters 6, 67 (1965); J. Appl. Phys. 37, 2922 (1966).
[17] J. C. Eidson and G. S. Kino, Appl. Phys. Letters 8, 183 (1966).
[18] D. K. Ferry, R. W. Young, and A. A. Dougal, J. Appl. Phys. 36, 3684 (1965).
[19] T. Musha, F. Lindvall, and J. Hagglund, Appl. Phys. Letters 8. 157 (1966).
[20] G. Bekefi, A. Bers, and S. R. J. Brueck, Phys. Rev. Letters 19, 24 (1967).

difference between stability and instability; hence, these exceptions are not considered significant as are those noted in the preceding paragraph. Indeed, the small number of $B=0$ exceptions are taken as evidence that the low J and E conditions in Fig. 4 are very near the real threshold of this effect; i.e., more sensitive detection systems would not reveal a lower threshold.

Radiation is also observed in the absence of a magnetic field well above threshold at high current levels, sufficient to produce plasma pinching.[5,21] A square-wave applied to sample H110-1 produces the I-E curve shown in Fig. 5. The shape of the curve (decreasing conductance) beyond ~1.5 A indicates that the plasma is pinched. Radiation is observed when the plasma conductance has the values indicated by the x's. The data of Fig. 4 are displayed as a shaded area in Fig. 5, with current as the ordinate rather than current density because the latter is unknown during pinching at the higher current levels.

In the sequence of events, as E is increased, injection is followed by impact ionization and then pinching. Lower resistivity crystals suffer pinching before impact ionization if an injected plasma is present (p-type), and in lower resistivity n-type it is impossible to obtain an impact-ionized plasma that is not at once in the pinched state. Since the high-quality sample H110-1 products gigahertz radiation during pinching, it is likely that any n- or p-InSb sample of comparable quality will also produce such radiation in the absence of applied magnetic fields.

Some emission conditions observed during the application of a square-wave voltage and a magnetic field between 600 G and 1.1 kG obtained using the other sample are also shown in Fig. 5. These results show that large E invariably produce conditions favorable for obtaining the radiation.

The curve labeled "milliamperes" in Fig. 5 reproduces the conductance characteristic of sample H110-1, the unusually-high-resistivity, high-mobility crystal during the beginning of plasma injection. These results are at variance with the existing theory of plasma injection into semiconductors[22] which predicts $I\propto E^2$ or E^3. Deviation from Ohmic conductance begins at 22 V/cm in sample H110-1, Fig. 5, and between that E and 95 V/cm, $I\propto E^{1.3}$. Beginning at 170 V/cm, $I\propto E^{5.0}$ until $E\approx 270$ V/cm.

IV. CONCLUSIONS

The results of Sec. III establish that gigahertz radiation is emitted by electron-hole plasmas in p-InSb at 77°K whose only external influence is an applied voltage capable of producing the appropriate conductance conditions. Obtaining the appropriate conditions apparently requires high-resistivity, high-mobility material.

An injected plasma, as contrasted with an impact-ionized plasma, is essential for determining the radiation threshold conditions because these occur at low current levels. The lowest plasma density observed to support radiation is 4×10^{11} cm^{-3}. Such low densities are not obtainable during the avalanching which accompanies impact ionization. Beyond threshold a pinched, therefore high-density, plasma has produced radiation, and it is expected that any high-density plasma subject to a sufficiently strong electric field strength will produce the radiation.

In previously reported work, magnetic field strengths were required to produce radiation from InSb. Two very different ranges in E accompany that radiation, one so high ($E>200$ V/cm) that plasmas are produced by impact ionization (in either n- or p-InSb), and the other so low ($E\geq 3$ V/cm) that a nonequilibrium plasma can play no role (again in either n- or p-type). The emission observed from impact-ionized plasmas requires a $B\geq 2$ kG[4,11–14] except in Morisaki and Inuishi's[15] report of "resonance-type" radiation with a threshold at ~900 G when observed with a 120-dB gain receiver. The low-E emission requires a $B\geq 1$ kG.[17–20] The summary of the conductances producing radiation given in Fig. 4(a) is therefore limited to conductance tuning by $B\leq 750$ G, in order to distinguish between the radiation occurring in the absence of a B and that previously reported as requiring a B. During the present experiments (utilizing thin slabs—see Table I) magnetic fields as large as 1500 G were employed with the only apparent difference in the results obtained compared with those for $B=0$ or $B\leq 750$ G being the exploration of the J-E plane at the higher E magnitudes as shown by Fig. 4(B). It is thus clear that the major influence of applied magnetic fields in the present experiments was conductance tuning.

Although the necessary and sufficient condition for obtaining radiation is simply obtaining an appropriate plasma conductance, if a magnetic field strength is applied to the plasma to force its conductance into the range required for radiation, production of proper plasma J-E conditions by itself is not sufficient for obtaining radiation. An explanation for the role of a relatively large magnetic field in helping produce the "high-E" emission[4,11–15] is given in another paper.[23] It is there concluded that the fundamental effect responsible for all the observed radiation does not require a magnetic field. This conclusion much simplifies the search for a theory capable of explaining all radiation from InSb except the resonance type.

The radiation decays more slowly than it builds up and can be observed in much reduced intensity even when most of the plasma has decayed.

[21] B. Ancker-Johnson, R. W. Cohen, and M. Glicksman, Phys. Rev. **124**, 1745 (1961).

[22] M. Lampert, in *Reports on Progress in Physics* (The Institute of Physics and The Physical Society, London, 1964), Vol. 27, p. 329.

[23] B. Ancker-Johnson, to be published in J. Appl. Phys.; available now in Boeing document No. D1-82-0623 (unpublished).

The simultaneous recording of current and radiation as a function of electric field strength produces many cases, like that in Fig. 3, which suggest that the instability responsible for the radiation affects the current magnitude.

The dependence of current on electric field during plasma injection (produced by square-wave voltages), Fig. 5, shows that more is to be learned and understood about injection of electron-hole pairs into semiconductors.

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Jahn-Teller Effect for a Single Vacancy in Diamondlike Covalent Solids

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The static Jahn-Teller effect is studied for a monovacancy V^+, V^0, and V^- in diamondlike covalent solids by a new method which applies to the case of linear combinations of atomic orbitals (LCAO) as wave functions. In this "rigid LCAO model" the orbitals are assumed to follow the nuclei rigidly in the deformation. The formal calculation is almost identical to that of the usual treatment of the Jahn-Teller effect by the perturbation method. For the vacancy in diamond we use the electronic structure determined by Coulson and Kearsley in a molecular model. We obtain energy lowerings of the order of 0.1 eV and distortion amplitudes of about 0.05 Å. Finally we compare our results with the experimental data.

INTRODUCTION

It is well known that optical absorption and electron paramagnetic resonance give evidence for the identification of some irradiation defects in diamondlike covalent solids as being vacancies and interstitials. But, in some cases, the question is which defect, either a single vacancy or an interstitial atom, is responsible for a given absorption band or EPR line. Theoretical work then is very useful to guide us in the interpretation of experimental data.

In order to explain the GR 1 absorption band, centered around 2 eV, Coulson and Kearsley[1] have studied theoretically the electronic states associated with a vacancy in a molecularlike model. In a similar way, Yamaguchi[2] has calculated the electronic structure for both vacancies and interstitial atoms. Unfortunately their results do not provide sufficient information to identify the observed centers with certainty.

From electron paramagnetic resonance we can get an idea of the symmetry properties of the defects. Actually there is a lowering of the tetrahedral symmetry due to the distortion of the neighboring atoms. In this work, we shall study that distortion in the case of single vacancies, as arising from static Jahn-Teller effect. Jahn and Teller[3] have shown that if an electronic state of a polyatomic molecule is orbitally degenerate, the nuclear configuration is unstable with respect to small displacements, unless the nuclei lie on a straight line.

It is then necessary to know the electronic structure of the vacancy. We shall first recall the method and results of Coulson and Kearsley, who made use of linear combinations of atomic orbitals (LCAO) for the wave functions. Because the first-order perturbation theory of the Jahn-Teller effect is not very convenient in this case, and it is probably better to assume that the wave functions are rigidly translated according to the atomic displacements, we propose in the second part a new treatment of the Jahn-Teller effect which we shall refer to as the "rigid LCAO model." A great advantage of this model is that the symmetry considerations of the perturbation theory are still valid and the formal results are similar.

In the third section, we shall give our numerical results and conclusions, and then review the experimental data and their interpretation. Finally, the two are compared with one another and with Watkins's

[1] C. A. Coulson and M. J. Kearsley, Proc. Roy. Soc. (London) **A241**, 433 (1957).
[2] T. Yamaguchi, J. Phys. Soc. Japan **17**, 1359 (1962).
[3] H. A. Jahn and E. Teller, Proc. Roy. Soc., (London) **161**, 220 (1937).