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Summary of Microwave Emission from InSb: Gross Features and Possible Explanations

Abstract: This paper reviews the experimental observations of microwave emission from InSb and the theories proposed to explain these. Two sources for some of the radiation, the acoustoelectric interaction and a collision-induced plasma instability, appear reasonably well established. Experiments are proposed to clarify a number of still unanswered questions.

Introduction

High frequency oscillations in the current passing through semiconductors and related microwave emission have been observed under many different conditions, as is evidenced by some of the experiments reported in this symposium. Much attention has been paid, in particular, to studies of InSb, which show oscillations in the range of some MHz[1,2] up to at least 102 GHz,[3,4] with a variety of experimental arrangements. Some of these observations have been reviewed by Ancker-Johnson.[5,6]

In this paper we will review the experimental observations and the theories proposed to explain them, and discuss two sources for the radiation which we believe to be reasonably well established. In the conclusion, some possible experiments will be suggested that may shed further light on the large number of unresolved questions.

Experiments

There is no need to attempt to explain all of the observations in terms of one[7] theoretical model; in fact, as we shall see, there are several experiments which fit two quite different sources. We shall, however, summarize the experimental situation as it is known at this time, as a framework for our further discussion.

Both n-[8] and p-type[9] InSb have shown microwave emission. Most experiments have been done at 77°K, but there have also been measurements at higher temperatures[18] (up to[29] 250°K) and some studies at 4.2°K as well.[18,24] The various observations may be divided into two groups, the "low-field" studies[43] with applied electric fields as low as 1 V/cm[46] being sufficient to produce observable radiation; and the "high-field" studies,[48] where at fields of 100 V/cm and higher, electron-hole pair production may also be occurring. Many of the studies have been done with magnetic fields applied; a given intensity of radiation appears to require a certain minimum electric field for a given magnetic field. However, there have been observations of radiation with no magnetic field applied,[50] but requiring substantially larger electric fields than those needed in the presence of a magnetic field.

The power level produced by the InSb is generally low, in the nanowatt range[44] or below for low-field studies, and in the microwatt range[3,40] for the high-field work. Since essentially none of the experimental configurations has achieved a high-efficiency coupling of the radiation to the detection system, the actual strength of the interaction is not known. Evidence for saturation or changes with power level probably arise from thermal effects on the semiconductor so that this area—the strength of the interaction—is still one to be fully explored by experiment.

A question which has been answered only in certain circumstances is that of the actual electron and hole densities present in the InSb during the radiation process. At high fields, impact ionization and injection are occurring, so that a two-component mobile plasma is present; in the case of the low field experiments with n-type InSb, the presence of holes is difficult to eliminate. In Wallace's experiments[31] with contactless samples there can be no contact injection; however, the geometry may encourage local impact ionization due to the combination of geometrical inhomogeneity and the usual growth inhomogeneities, a factor which must be considered, as emphasized by Thompson and Kino.[52] They note the substantial enhancement of electric-field inhomogeneity

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near the contact in the presence of transverse or longitudinal magnetic fields, because of the large electron mobility. The studies reported in this meeting by George and Bekefi[53] show that the presence of injecting contacts facilitates the radiation's appearance, but these studies are not sufficiently quantitative to be used in testing several possible theories.

The role of the magnetic field was deemed important in many of the early studies, in which effects were observed in transverse magnetic fields[54] or in longitudinal magnetic fields,[55] and in many cases at some angle other than 0 or 90°. The facts that the same type of "noise" radiation is observed in the absence of magnetic fields,[50] and that there is at least one theory[56,57] that predicts results in agreement with experiment and does not require a magnetic field in the basic interaction, support the suggestion[7] that the magnetic field may not be essential to the radiation-producing mechanism. Some component of transverse magnetic field (difficult to avoid in the best "longitudinal" experiments because of contact effects and inhomogeneities) is sufficient to deflect a mobile plasma to one surface, and concentration of the plasma may be the vital function of the applied magnetic field.

With regard to the observed frequencies, we note that most of the experiments have reported that radiation exhibits a practically monotonic decrease in intensity with increase in frequency,[3,4] although there have been some reports of structure.[22,25] A number of studies report "resonant" radiation, in the sense that "narrow band" radiation ($\Delta f/f \lesssim 1\%$) is observed.[58] However, in most of these cases the narrowness of the radiation is measured in terms of a tuning magnetic field, rather than directly in the frequency spectrum. In their experiments Swartz and Robinson[51,59] perturbed the surface layer by a notch of about $\lambda/2$ in length, and this agreed fairly well with the dispersion relation for the waves they believe to be responsible for emission in their material. The measurements of Platts and Bers[60] also give some measure of the wave-dispersion relation, indicating a group velocity comparable to the electron drift velocity. Intriguing and still unexplained are the observations of Bekefi, Bers and Brueck[24] at 4.2°K, with the structure showing a regular, linear dependence on the magnetic field.

There has been a number of experiments attempting to relate the concurrent observation of low-frequency (MHz) and microwave emission. In some cases there is evidence for the presence of acoustoelectric domains in the crystals[32,36,46] and for emission that occurs at the time one of the domains strikes the anode,[37] even when the applied electric field has been cut off. We shall discuss the relation between the acoustoelectric interaction and the radiation just below; it should be noted that the time-dependence of the radiation can assist in separating out mechanisms, provided the important factors—temperature,[40] lifetime, possible trapping effects—are sufficiently well known. In the work of van Welzenis and van den Dries,[30] the emission was observed only during a small part of the time of pulse application to the InSb, which the authors believe was a time of plasma formation. However, in strong transverse magnetic fields, they failed to see emission accompanying the plasma formation process.

Many of the observations involving magnetic fields have shown rather strong angular dependences of the emission intensity on the magnetic-field orientation with respect to the applied current. However, in none of the experiments is it clear that such a dependence is a vital factor—although the orientation may have some influence on the occurrence of impact ionization, on the rate of plasma transport to particular surfaces, on the gain of acoustic-wave interaction with the electron flow, on the spatial variation of plasma density, and many other effects. Consequently, it is difficult, if not impossible, to draw definitive conclusions from such observations. In order to do better, the influence of actual physical geometry and inhomogeneities must be removed from the experiments. It is hoped that future work will succeed in this objective.

Theories

The report[3] of the observation of microwave radiation set off proposals of a variety of mechanisms to explain the experiments. However, in only a limited number of cases has there been an attempt to compare the results of the theory with experiment. The problem in so doing has been that in many cases the experimental conditions have not been sufficiently well defined to allow such comparison. Such parameters as the densities of electrons and holes, their spatial variation and the spatial variation of the electric field in the InSb have not been known to the experimentalists sufficiently well, in many cases, to allow good tests of the theories.

We will first briefly mention a number of interesting theories which have been proposed, and which would appear to us not to be involved in the experimental observations. These include the two-stream excitation of helicons,[61,62] the photoconductive mixing[63] of amplified spontaneous radiation at the band gap, and the proposed impact-ionization instability in pure electric[64] and crossed electric and magnetic fields.[65] Little evidence is available to link any of these with the observed radiation.

We have a second group of mechanisms that may not be so easily eliminated, since any or several of them may actually be involved either primarily or secondarily in producing the microwave emission. These include helical instability in a longitudinal magnetic field,[5,66] gradient-induced density instabilities,[49,67] a suggested form of surface relaxation involving the flow of plasma to the semiconductor surface,[7] and the several suggestions made recently that require some local breakdown[52,53] and production of a mobile electron-hole plasma, even in the case where the average electric field is quite low. The occurrence of the helical instability is well documented, both for injected and impact-ionization-produced plasmas, but the frequencies are in the MHz range, so that the presence of high-frequency emission would require conversion by some nonlinear operation in the semiconductor.* The occurrence of local breakdown in samples with low average electric fields in a transverse magnetic field has been noted.[52] In this latter case, we still need to explain the source of the emission, but we would be able to use the same source for both low- and high-field observations.

In addition to those mechanisms just described, there are two which have been discussed and documented experimentally that would appear to be responsible for the bulk, if not all, of the observed emission. These two are the acoustoelectric interaction[68] and the broad class of two-stream plasma waves,[79] where in the latter case a growth instability resulting from the presence of collisions (collision-induced) seems to show good agreement[51,59] between experiment and theory. The theory provides for three geometries in which such waves may be observable: bulk plasma waves, surface plasma waves and, in the third case, a thin layer of plasma. The last case seems to be that most likely to be responsible for the observed emission in Swartz and Robinson's experiments.

Experimental and theoretical confirmation

The acoustoelectric interaction in InSb has been studied by a number of workers.[85] It has been shown in a number of recent experiments[36,46] that the characteristics of two dependencies, that of the acoustoelectric oscillations (involving sound-wave carrying domains) and that of the microwave emission, on the applied electric and magnetic fields are strikingly similar. This holds for both long and short-wavelength classes of interaction. These observations pertain to the case of "low-field" emission, and they also require that the samples be sufficiently long (of the order of 1 cm) for the gain to be large. At stronger electric fields (or magnetic fields), the increased gain could also allow growth of high-frequency acoustic waves through round-trip gain[92] in shorter samples. Although the correlation is still semi-*quantitative*, it is sufficiently impressive to suggest that *some* of the observed radiation must involve the acoustoelectric interaction. What is not clearly understood[36,46] at the present time is which of a number of mechanisms for coupling out electric energy at the microwave frequencies is involved.

Similarly, the experiments of Swartz and Robinson[51] are examples of the kind of approach that should be employed in trying to evaluate mechanisms for the microwave emission. They are able to present a number of points for testing of their theory of a two-stream, collision-induced instability: the electron and hole densities, the magnetic field necessary for a given density, and the frequency and the wave dispersion. Although quantitative data of this nature are difficult to obtain, it is heartening to note the increasing availability of such correlatable information from several laboratories. It would then appear to be clear that there is a collision-induced instability producing powers of microwave emission of the order of those observed by many others, and that the noise-character (as contrasted with the Swartz–Robinson "coherent" emission present in cases where there is a perturbation on the surface of an appropriate geometrical form and size) may arise from the same source. A similar mechanism is the one studied by Burke and Kino[33] with regard to lower-frequency surface waves.

Suggestions for the future

Although two mechanisms have been identified as being likely explanations for some of the observed emissions from InSb, there remain other possibilities, and a number of unanswered questions. The possibility that inhomogeneity may be involved in the low-field work leaves available the option that the two-stream instability may be operating in this case as well, although now arising from local plasma concentrations. To test this, experiments on the low-field emission should be performed under conditions where the presence and spatial distribution of local plasma concentrations or injection can be definitely evaluated.

The recent work of Nanney and George[93] on BiSb alloys, and their intriguing suggestion regarding electron-injection spin pumping of paramagnetic impurity states should be investigated with regard to its relevance to some of the "resonant" and magnetic-field-sensitive narrow band radiation that has been observed in InSb, especially at 4.2°K. Deliberate doping studies may prove worthwhile in testing such a suggestion.

In summary, experimental investigation of carrier densities, homogeneity, the effect of magnetic field orientation on these, the dispersion relation in InSb of the

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* Note added in proof. T. Musha, J. Ohnishi and M. Hirakawa, *Phys. Rev. Lett.* 22, 1254 (1969), have suggested that their observed "low-field" microwave radiation is due to the helical instability in a short, small (about 10μm in diameter) filament of electron-hole plasma near one non-ohmic contact. The functional dependence on the magnetic field of their experimental values for the microwave frequency at threshold agrees with a previous theory for the helical instability, M. Glicksman, *Phys. Rev.* 124, 1655 (1961). The values Musha, et al. assume for the electron-hole plasma properties in order to provide *quantitative* agreement are of a reasonable order, but quite probably not accurate, just as the theory they use involves assumptions violated in their model.

microwave and other-frequency energy present, contact effects and the influence of paramagnetic impurities should help to further clear up a field of research which has attracted much interest because of its puzzles. The currently active attack on a number of these problems is promising evidence for future progress. The continuing need for good coupling between the experimental work and a theoretical treatment is paramount. The likelihood that the experiments will provide insight is questionable when they are not inspired by or being directly used in a theoretical analysis, at least at this stage of our research on this subject, now some five years old.

References

1. M. Toda, *Japan. J. Appl. Phys.* **2,** 776 (1963).
2. M. Glicksman, *Plasma Effects in Solids, Paris, 1964,* Dunod, Paris, 1965, p. 149.
3. R. D. Larrabee and W. A. Hicinbothem, Jr., *Plasma Effects in Solids, Paris, 1964,* Dunod, Paris, 1965, p. 181.
4. T. O. Poehler, J. R. Apel and A. K. Hochberg, *Appl. Phys. Lett.* **10,** 244 (1967).
5. B. Ancker-Johnson, *Semiconductors and Semimetals 1,* Academic Press, New York City, 1966, p. 379.
6. B. Ancker-Johnson, *Proceedings IX International Conference on the Physics of Semiconductors, Moscow, 1968,* Nauka, Leningrad 1968, p. 813.
7. B. Ancker-Johnson, *J. Appl. Phys.* **39,** 3365 (1968).
8. *Op. cit.* (1, 3, 4, 10–37).
9. *Op. cit.* (3, 7, 11, 14, 18, 23, 26, 38–42).
10. H. Ikoma, *J. Phys. Soc. Japan* **19,** 419 (1964).
11. L. Auchterlonie, *Electronics Lett.* **1,** 262 (1965).
12. S. J. Buchsbaum, A. G. Chynoweth and W. L. Feldmann, *Appl. Phys. Lett.* **6,** 67 (1965).
13. D. K. Ferry, R. W. Young and A. A. Dougal, *J. Appl. Phys.* **36,** 3684 (1965).
14. K. Suzuki, *Japan. J. Appl. Phys.* **4,** 42 (1965).
15. T. Suzuki, *Japan. J. Appl. Phys.* **4,** 700 (1965).
16. M. Toda, *Japan. J. Appl. Phys.* **4,** 854 (1965).
17. J. C. Eidson and G. S. Kino, *Appl. Phys. Lett.* **8,** 183 (1966).
18. R. D. Larrabee and W. A. Hicinbothem, Jr., *IEEE Trans. Electron Devices* **ED-13,** 121 (1966).
19. H. Morisaki and Y. Inuishi, *Japan. J. Appl. Phys.* **5,** 343 (1966).
20. H. Morisaki and Y. Inuishi, *Japan. J. Appl. Phys.* **5,** 637 (1966).
21. T. Musha, F. Lindwall and J. Hagglund, *Appl. Phys. Lett.* **8,** 157 (1966).
22. K. Suzuki, *IEEE Trans. Electron Devices* **ED-13,** 132 (1966).
23. B. Ancker-Johnson, *J. Phys. Soc. Japan* **22,** 1156 (1967).
24. G. Bekefi, A. Bers and S. R. J. Brueck, *Phys. Rev. Lett.* **19,** 24 (1967); *IEEE Trans. Electron Devices* **ED-14,** 593 (1967).
25. D. K. Ferry, R. W. Young and A. A. Dougal, *Z. Naturforsch.* **22a,** 576 (1967).
26. H. Ikoma, *Japan. J. Appl. Phys.* **6,** 1226 (1967).
27. A. N. Kohn, *Proc. IEEE* **55,** 695 (1967).
28. H. Morisaki and Y. Inuishi, *J. Phys. Soc. Japan* **23,** 269 (1967).
29. T. O. Poehler, *Appl. Phys. Lett.* **10,** 356 (1967).
30. R. G. van Welzenis and J. G. A. M. van den Dries, *Appl. Phys. Lett.* **11,** 374 (1967).
31. R. N. Wallace, *MIT Res. Lab. Electronics QPR No. 87* Oct. 15, 1967.
32. T. Arizumi, T. Aoki and K. Hayakawa, *J. Phys. Soc. Japan* **23,** 1251 (1967).
33. B. E. Burke and G. S. Kino, *Appl. Phys. Lett.* **12,** 310 (1968).
34. D. K. Ferry, R. W. Young and A. A. Dougal, *IEEE Trans. Electron Devices* **ED-15,** 337 (1968).
35. W. A. Porter and D. K. Ferry, *Proc. IEEE* **56,** 1625 (1968).
36. T. Arizumi, T. Aoki and K. Hayakawa, *J. Phys. Soc. Japan* **25,** 1361 (1968).
37. T. Arizumi, T. Aoki and K. Hayakawa, *J. Phys. Soc. Japan* **26,** 370 (1969).
38. H. Ikoma, I. Kuru and K. Hataya, *J. Phys. Soc. Japan* **19,** 238 (1964).
39. B. Ancker-Johnson, *J. Phys. Soc. Japan* **21** *Suppl.* 694 (1966).
40. G. A. Swartz and B. B. Robinson, *Appl. Phys. Lett.* **9,** 232 (1966).
41. B. Ancker-Johnson, *Phys. Rev.* **164,** 1050 (1967).
42. B. Ancker-Johnson, *Appl. Phys. Lett.* **10,** 279 (1967).
43. *Op. cit.* (12, 13, 17, 21, 24, 25, 31, 32, 34–37, 44–47).
44. A. G. Chynoweth, S. J. Buchsbaum and W. L. Feldmann, *J. Appl. Phys.* **37,** 2922 (1966).
45. E. V. George, *MIT Res. Lab. Electronics QPR No. 88,* Jan. 15, 1968, p. 202.
46. C. W. Turner, *J. Appl. Phys.* **39,** 4246 (1968).
47. C. W. Turner and J. Crow, *Appl. Phys. Lett.* **11,** 187 (1967).
48. *Op. cit.* (1, 3, 4, 10, 11, 14, 15, 18–20, 22, 23, 26–30, 38–42, 49).
49. T. Suzuki, *IEEE Trans. Electron Devices* **ED-13,** 202 (1966).
50. *Op. cit.* (25, 30, 32, 36, 37, 41, 42, 51).
51. G. A. Swartz and B. B. Robinson, *J. Appl. Phys.* **40,** (July 1969).
52. A. Thompson and G. S. Kino, *IBM J. Res. Develop.* **13,** XXX (1969, this issue).
53. E. V. George and G. Bekefi, *Appl. Phys. Lett.* **15,** 33 (July 1, 1969).
54. *Op. cit.* (1, 3, 4, 7, 11, 13–16, 19, 20, 22, 25–29, 31, 33–37, 46, 47, 49).
55. *Op. cit.* (3, 4, 7, 12, 14, 16, 18, 21, 22, 24, 35, 44, 45).
56. B. B. Robinson, *RCA Rev.* **28,** 366 (1967).
57. B. B. Robinson and G. A. Swartz, *J. Appl. Phys.* **38,** 2461 (1967).
58. *Op. cit.* (17, 19–21, 24, 28, 40, 45, 51).
59. B. B. Robinson and G. A. Swartz, *IBM J. Res. Develop.* **13,** XXX (1969, this issue).
60. D. A. Platts and A. Bers, unpublished.
61. J. Bok and P. Nozieres, *J. Phys. Chem. Solids* **24,** 709 (1962).
62. M. C. Steele, *Plasma Effects in Solids, Paris 1964* Dunod, Paris 1965, p. 189.
63. M. C. Steele, *RCA Rev.* **27,** 263, (1966).
64. M. Toda, *J. Appl. Phys.* **37,** 32 (1966).
65. M. Toda, *J. Appl. Phys.* **37,** 37 (1966).
66. K. Ando and M. Glicksman, *Phys. Rev.* **154,** 316 (1967).
67. T. Suzuki, *J. Phys. Soc. Japan* **21,** 2000 (1966).
68. *Op. cit.* (36, 69–78).
69. K. Blotekjaer, *Ericsson Technics* **2,** 127 (1966).
70. M. C. Steele, *RCA Rev.* **28,** 58 (1967).
71. G. S. Kino and R. Route, *Appl. Phys. Lett.* **11,** 312 (1967).
72. C. W. Turner, T. van Dugen and K. Weller, *Electronics Lett.* **3,** 162 (1967).
73. Y. Abe and N. Mikoshiba, *Appl. Phys. Lett.* **13,** 242 (1968).
74. H. N. Spector, *Phys. Rev.* **165,** 562 (1968).
75. C. Hammar and P. Weissglass, *Appl. Phys. Lett.* **13,** 219 (1968).

76. Yu. M. Galperin and V. D. Kagan, *Fiz. Tverd. Tela* **10,** 2037 (1968); *Sov. Phys.-Solid State* **10,** 1600 (1969).
77. J. Gorelik, B. Fisher, B. Pratt and Z. Lug, *Phys. Lett.* **28A,** 485 (1966).
78. W. Harth and R. Jaenicke, *Appl. Phys. Lett.* **14,** 27 (1969).
79. *Op. cit.* (33, 49, 51, 56, 57, 67, 80–84).
80. W. Kochner, *Arkiv. der Elektrisch. Ubertrag.* **19,** 445 (1965).
81. B. Vural and M. C. Steele, *Phys. Rev.* **139,** A300 (1965).
82. P. Gueret, *J. Appl. Phys.* **39,** 2136 (1968).
83. P. Gueret, *J. Appl. Phys.* **39,** 3225 (1968).
84. G. S. Kino, *Appl. Phys. Lett.* **12,** 312 (1968).
85. *Op. cit.* (32, 36, 37, 46, 47, 71, 73, 75, 77, 86–91).
86. R. Bray, C. S. Kumar, J. B. Ross and P. O. Sliva, *J. Phys. Soc. Japan* **21** *Suppl.* 483 (1966).
87. M. Kikuchi, H. Hayakawa and Y. Abe, *Japan. J. Appl. Phys.* **5,** 1259 (1966).
88. M. Kikuchi, H. Hayakawa and Y. Abe, *Japan. J. Appl. Phys.* **5,** 1260 (1966).
89. J. P. Martin, J. B. Mead and L. Witten, *Bull. Am. Phys. Soc.* **13,** 709 (1968).
90. K. W. Nill, *Phys. Rev. Lett.* **21,** 82 (1968).
91. C. W. Turner, *IBM J. Res. Develop.* **13,** 611 (1969, this issue).
92. R. Bray, *IBM J. Res. Develop.* **13,** 487 (1969, this issue); V. Dolat, J. B. Ross and R. Bray, *Appl. Phys. Lett.* **13,** 60 (1968).
93. C. A. Nanney and E. V. George, *Phys. Rev. Lett.* **22,** 1062 (1969).

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