Review Article: Parametric Interactions in Nonlinear Semiconductor Plasma

Kirti Sontakke [*], S. Ghosh [**]

[*] School of Studies in Physics, Vikram University Ujjain, Madhya Pradesh, 456010, India
[**] School of Studies in Physics, Vikram University Ujjain, Madhya Pradesh, 456010, India

Abstract- We review publications on Parametric Interactions in nonlinear semiconductor plasma. Topics covered are Hydrodynamical Model of Plasma, Parametric Excitation and Amplification, Piezoelectric Semiconductors, Ion-Implantation, Laser-Plasma Interaction.

Index Terms- Wave interactions in nonlinear optics, Parametric excitation, Diffusion, II order Susceptibility.

I. Introduction

We have presented an introduction to Parametric interactions (PI) in Nonlinear semiconductor plasma. This review focused on the basic experimental facts and the essential features of the mechanisms which have been proposed to account for observations. We then review very recent fundamental development that includes Diffusion, Acousto-Helicon waves, Quantum Plasma etc.

In nonlinear wave propagation, the analysis of interaction depending on a particular physical situation is of great importance. As a consequence of nonlinear interactions between matter and wave, there arises phenomenon such as Parametric, Modulation and Stimulated scatterings to name a few. The most fundamental interaction is the PI. The understandings of these phenomena have lead to their successful application in the field like laser technology, laser spectroscopy, optical communication, photo physics, Photochemistry, Material Processing etc. It is well known fact that the study of matter wave interaction provides a tremendous insight that is helpful in analyzing the basic properties of the medium. Therefore the principle aim of this report is to study (PI) in a nonlinear semiconductor plasma (NLSP). PI was discovered fifty years ago. The field developed aggressively, even explosively for the first decade and then settled down a bit as entered its teenage years. Interest shifted from fundamentals to applications and a steady state stream of papers was published in diverse fields which included Solid state plasma, Nano structures, Quantum Plasma or even Medicine. As PI enters its third decade there has been a renewed interest in fundamentals especially in PI of low frequency waves particularly in semiconductor plasmas. Few scientists twenty five years ago would have bet the PI notoriously for its difficulty and insensitivity at that time.

We present here a contemporary review of PI with two objectives in mind. First we wish to provide an introduction to the field for scientist and for students, in particular who may wish to conduct research in this area. Second, we wish to highlight new areas of PI research which we feel are particularly exciting and show promise for further development. Our goal is to provide the reader with sufficient background, orientation and perspective to read.

The review is organized as follows. The elementary aspects of PI are described from the research papers. A short history of the discovery of PI is followed by the key experimental facts. The theoretical formulation is based on Hydro dynamical Model of plasma using coupled mode theory and the Parametric Amplification is obtained in the form of gain. With the help of second order Susceptibility the gain characteristics area analyzed. This review article focuses the effects of different plasma parameters on parametric excitation.

I. HISTORY AND FUNDAMENTALS

Parametric amplification and oscillation in the radio frequency and microwave range were developed before the laser was invented [1]. After the advent of laser PI, the origin of which lies in the II order susceptibility $\chi^{(2)}$ of the medium has emerged as one of the most significant subfield of nonlinear Physics. It is an important mechanism of nonlinear mode conversion from high to low frequency waves and vice versa. It is also one of the key processes to generate coherent radiation at new wavelength in the range from extreme ultraviolet to millimeter to millimeter not available from direct sources. These phenomena can well explained in terms of bunching of free carriers present in the medium, under the influence of the fields applied externally and those associated with generated wave [2]. As an inverse process of sum frequency generation the general theory of parametric amplification is same that of the difference frequency generation and is generally known as parametric conversion process. It has since become an important effect because it allows the construction of widely tunable coherent infrared sources through the controllable decomposition of the pump frequency.

II. Plasma in Semiconductors

The concept of plasma in solid semiconductors is used to describe the collective response of a quasi-neutral system consisting of free charge carriers of two signs and ionized impurity atoms also of two signs to electromagnetic perturbations. The medium for charge carriers in solids is characterize by high value of dielectric constant which makes it possible to ionize atoms easily and to realize the plasma state even at a very low temperature. Such ionized, plasma are rigidly connected with the lattice. The plasma containing one kind of mobiles carriers is also frequently, since the presence of a compensating charge of the opposite sign is always assumed. When plasma contains more than one kid of mobile particles is it called multi component, other names for the intrinsic plasma are compensated, neutral and mobile. The fundamental difference between the plasma in solid and the gaseous plasma is that in solids the motion of mobile charges [charge carriers] of the plasma under the action of external forces occurs not as that of free particles but first under the condition of strong interaction with the field of atom that form the lattice and second in the presence of intense friction resulting from numerous collision with defect and vibration of crystalline lattice [3].

III. HYDRODYNAMICAL MODEL

The possibility of parametric amplification of acoustic wave is because of the coupling that, the driving pump electric field introduces between the acoustic waves (AW) and Electron Plasma wave (EPW). An acoustic perturbation in the lattice gives rise to an electron density fluctuation in the medium at the sum frequency. These couples nonlinearly with the pump field and drive the EPW at the sum and difference frequencies.

The electron density perturbation, in turn, couples nonlinearly with external field and may reinforce the original perturbation at the acoustic frequency. Thus under certain conditions the AW and APW drive each other unstable at the expense of the pump electric field. In the present review parametric interaction is taken into consideration. This model proves to be suitable for the present study as it simplifies analysis by the authors, without any loss of significant information by replacing the streaming electrons with an electron fluid described by few macroscopic parameters like average carrier density, average velocity etc. however it restricts analysis by the author to be valid only in the limit ($kl \langle\langle\langle (1)$) k the wave no, and l is the mean free path. The non uniformity of the high frequency electric field could be neglected under the dipole approximation when the excited idler and signal waves have wavelength which are very small as compared to the scale length of electromagnetic field variation [4]. Therefore, in the absence of k_0 , the Doppler shift due to travelling space charge wave disappears. The PI of the pump generates an AW at (ω_a, k_a) and scatters a side band wave (SBW) at (ω_1, k_1) supported by the lattice and electron plasma in the media, by considering the basic equation such as continuity polarization, equation of motion and momentum transfer equation and following the mathematical formulation of Ghosh et al. [5-6] the slow and fast components are analyzed to obtain slow and fast component of perturbed electron densities, and thus the nonlinear current density is valuated to find out the induced polarization.

IV. POLARIZATION AND II ORDER SUSCEPTIBILITY

In this area of research the first break though was achieved in 1961 when a pulsed laser beam was sent into a piezoelectric crystal. Franken and his co-worker [7] for the first time in history of optics observed second harmonic generation at the optical frequency shortly after this discovery several other frequency mixing effects were observed. The researcher [8] released that all these new effects could be explained if the linear term on right had side of equation (1) be replaced by a series in ascending power of applied field E_0

$$P = \varepsilon_0 [\chi^{(1)} E_0 + \chi^{(2)} E_0 E_0 + \chi^{(3)} E_0 E_0 E_0] \qquad (1)$$

The first term containing the 1st order susceptibility describes the familiar linear optical effect. Franken experiment [6] confirmed the existence of the II term where as Kaiser and Garrett [9] observed cubic nonlinearities explaining the $\chi^{(3)}$ terms.

In equation (1) the polarization expansion is convergent as successive products of electric field satisfy the condition $\chi^{(1)} \rangle \chi^{(2)} \rangle \chi^{(3)}$ and so on. The linear optical susceptibility $\chi^{(1)}$ gives rise to the linear response of the material and includes absorption emission and refraction of light. The second order optical susceptibility $\chi^{(2)}$ give rise to three wave mixing phenomena such as second harmonic generation, DC rectification [10], Pockels effect, Parametric Amplification and Oscillation [11], Sum and Difference Frequency Generation [12-13] and so on. The phenomena of PI play a distinctive role in nonlinear optics. It is totally accepted fact that the origin of PI lies on the second order nonlinear optical susceptibility $\chi^{(2)}$ of the medium. Flytzanis [14] and Pietons [15] have respectively studied $\chi^{(2)}$ in different frequency region and the sum rules for the nonlinear susceptibility in solids and other media. Up till now experiments [16-18] have been performed concerning the behaviour of $\chi^{(2)}$, but neverth less the agreement between theory and experiments can be said to the poor.

V. EFFECT OF PLASMA PARAMETERS ON PARAMETRIC INTERACTIONS

There are numerous excellent reports on effect of plasma parameters on PI of different types of waves in semiconductor plasma [19-23] the basis of the amplification of ultrasonic waves due to dc electron streaming in Piezoelectric semiconductor has been studied in great detail in past years [24-25]. The application of high frequency filed with `$\omega_o = \omega_p$ can lead to coupling between ultrasonic waves and electron plasma waves in piezoelectric semiconductors [26] and leads to instability when a critical value is exceeded. Thus the basic conclusion comes out that it is possible to amplify ultrasonic waves in piezoelectric semiconductors with currently available pulsed high frequency fields.

In this review we have given the advancement of PI in semiconductor plasma. In this series we review the PI of acousto-helicon waves in a piezoelectric semiconductor which had been studied by the Guha et al. [27]. A number of papers stress the parametric excitations of helicon waves [28]. Parametric Excitation of a helicon wave in magneto active electron plasma by amplitude, modulating the pump wave at an appropriate frequency was studied by Paverman Taskhakaya [29]. Pavlovich and Epshtein [30] studied the behaviour of acousto-helicon waves in a strong high frequency oscillatory electric field. Guha et al. [27] thus concluded that growth rate depends on B_0 and increases as square of the magnetic field which is in agreement with ref. [31].

The researcher of the same group has predicted the parametrically excited instability of Hybrid mode in magnetized semiconductors [32]. They showed that parametric decay of a laser beam into an ultrasonic wave and another electromagnetic wave results in PI of hybrid mode. The magneto-statics field couples the acoustic and electromagnetic waves and in its absence the instability disappears. The growth rate increases with the square of magnetic field. The presence of deformation potential enhances the growth rate. The results of above referred paper are in well agreement with the threshold electric field value reported by S. Guha and N. Apte [33]. Another result based on PI is reported by S. Ghosh and V. K. Agrawal [34] point out the parametric decay of a laser beam into Ultrasonic and Helicon waves in longitudinally magnetised semiconductors. They have studied the hydrodynamical model of homogeneous plasmas, the parametric decay of a laser beam into an Ultrasonic wave and a Helicon wave has been studied in heavily doped n-type semiconductors in the presence of longitudinal magnetostatic field. This decay process results in the parametric excitation of acousto-helicon waves. The above report reported by Ghosh et al. is having crucial applications in microwave devices based on the parametric excitation and playing an important role as low noise amplifiers and oscillations. There are many research papers which stresses such interaction in microwave devices [35-38].

The present review highlights the parametric instabilities of laser beams in material with strain dependent dielectric constant [39]. In the above referred paper it is found that anomalously large values of growth can be obtained for materials with large values of the dielectric constant which otherwise cannot be achieved with piezoelectric interaction. They have done the estimations for $BaTiO_3$ crystal irradiated with a pulsed 10.6 μm CO_2 laser. S. Sharma [40] shows the Acousto Helicon coupling in Semiconductors and Ogg [41] have pointed out that in the presence of an electrostatic field, Ferroelectric crystals with high dielectric constant can have anomalously large values of linear gain constant, which is otherwise not achievable with piezoelectric interactions. Earlier PI of waves has been extremely studied in the last four decades there are tremendous possibilities of further exploration and exploitation due to poor agreement between theories and experiments. The current trends in the field indicate that this old but fascinating phenomena is still hotly pursued by both theoretician as well as experimentalists and increasing number of interesting application exploiting PI are being discovered or yet to be discovered [42].

In most of the investigations referred above effect of carrier diffusion which is responsible for the nonlinear refractive index change, has not been discussed. So we have reviewed here the research article of Ghosh et al. [43]. They have showed the effect of carrier diffusion on PI. In their investigation they found that the wave number k is greatly influenced by carrier concentration and diffusion of the carriers may induce appreciable large second order nonlinearity in a diffusive Centro-symmetric semiconductor. This nonlinearity may be termed as diffusion induced second order (DISO) nonlinearity and may lead to interacting waves. The interesting feature of DISO nonlinearity may play an extremely important role in operation of parametric amplifiers, oscillators, tunable radiation sources. Thus from the above discussion it is concluded that as the DISO nonlinearity maximizes whereas required inciting intensity minimizes at resonance frequency. This fascinating and unique feature of DISO nonlinearity may reduce the operating cost of parametric amplifier and other non linear devices based on this principle. Hence the review of this article focuses your attention towards the diffusion induced second order nonlinearity may play an extremely important role in construction of parametric amplifiers, oscillators, tunable radiation sources etc.

Few papers deal with the parametric interactions in ion-implanted plasma [44-46]. Very recently the researcher from the same group of above referred papers has explored the possibility of PI in the ion-implantation. They have considered the well known hydrodynamical model of homogeneous ion-implanted n-type semi conductor plasma with electrons and negatively charged colloids as carriers subjected to an electromagnetic pump wave and an external magnetic field under thermal equilibrium. Normally the ion-implanted semi conductor plasma and its response to an applied field is treated quantum mechanically. The author neglected the non uniformity of the high frequency pump field under dipole approximation under the excited acoustic wave have wave length which are very small compared to the scale length of electromagnetic field variation. The author has considered the colloids rich piezoelectric semi conductor plasma as a medium under study with a view to control the parameters without much difficulty. Thus it is found that in the presence of the implanted colloids the imaginary part of colloids susceptibility does not show any modification in the instability characteristics of wave spectrum. Hence the presence of colloids is responsible for the effective modifications in the dispersion characteristics of acoustic wave in ion-implanted semi conductor plasma. A significant enhancement in the parametric dispersion can be achieved by the proper selection on doping level pump field and appropriate wave number. The above result is having great potential applications in soft condensed matter of long ranged ordered structures which may be formed with protein, nucleic acids, viruses and other biological macro molecules and also in ion-implanted techniques.

Very recently Ghosh et al. [47] explore the quantum effect on parametric amplification characteristics. They have employed the Quantum Hydrodynamical model (QHD) for the electron dynamics in the semi conductor plasma and predicted the parametric interaction of a laser radiation in an unmagnetised piezoelectric semi conductor plasma. It is found that the Bhom potential in the electron dynamics enhances the gain coefficient of parametrically generated modes where as reduces the threshold pump intensity. QHD have been developed by Haas et al. [47-48], the versatility of this approach is a promising development for analytical applications.

VI. CONCLUSION AND OUTLOOK

PI research continues at brisk pace; hundreds of papers are published each year. Fundamental aspects of the phenomenon are still under investigation. Above we have reviewed the important work done by prominent authors in the area of PI in non linear semi conductor plasma. Hence from the above referred work we concluded that Parametric interaction in nonlinear semiconductor plasma is an efficient tool for the fabrication of optoelectronic devices such as optical parametric oscillators, optical resonators etc.

REFERENCE

[1] W. H. Louisell, "Coupled Mode and Parametric Electronics ",Wiley, New York, 1960.

[2] E. M. Conwell and A. K. Ganguli, " Mixing of Acoustic Wave in Piezoelectric Semiconductors", Phys. Rev. B **4,** 1971, pp. 2535-2558.

[3] L. A. Artsimovich, "Elementary Plasma Physics", Blaisdell, New York, 1965.

[4] A. Neogi and S. Ghosh, " Parametric Amplification in Magnetised Piezoelectric Semiconducting Plasmas"' Phys. Stat. Sol. (b) **152,** 1989, pp. 691-700.

[5] G. Sharma and S. Ghosh, " Modulational interactions in Magnetised Piezoelectric Semiconductor Plasma", Euro. Phys. J. D **11,** 2000, pp. 301-307.

[6] P. A. Franken, A. E. Hill, C. W. Peters and G. Weinreich, " Generation of Optical Electronics", Phys. Rev. Lett. **7**, 1961, pp. 118-119.

[7] J. A. Armstrong, N. Bloembergen, J. Ducling and P. S. Pershan, " Interaction between Light Waves in Nonlinear Dielectrics",Phys. Rev. **127,** 1962, pp.1918-1939.

[8] M. Bass, P. A. Franken, A. E. Hill, C. W. Peters and G. Weinreich, "Optical Mixing", Phys. Rev. Lett. **8**, 1962, pp.18 .

[9] W. Kaiser and C. G. B Garret, "Two Photon Excitation in CaF_2 :Eu^{2+}. Rev. Lett. **7**, 1961, pp.229-231 .

[10] M. Bass, P. A. Franken, J. F. Ward and G. Weinreich, "Optical Rectification", Phys. Rev. Lett. **9**, 1962, pp. 446-448.

[11] J. A. Giordamain and R. C. Miller, " Tunable Coherent Parametric Oscillation in LiNbO at Optical Frequencies"' Phys. Rev. Lett. **14**, 1965, pp. 973-976.

[12] K. E. Neihuhr, " Nonlinear Optical Properties of Some Semiconductors with Selenium Compounds", Appl. Phys. Lett. **2**, 1963, pp.136-137 .

[13] A. W. Smith and N. Braslau, " Observation of an Optical Difference Frequency", J. Appl. Phys. **34,** 1963, pp.2105-2106 .

[14] C. H. Flytzanis, "Quantum Electronics", Eds. H. Rabin and C. L. Tang Academic press, New York, 1975.

[15] K. E. Peiponen, " On the Derivation of Sum Rules For Physical Quantities and their Applications for Linear and Non-Linear Constants", J. Phys. C **20**, 1987, pp.2785 .

[16] F. Bechstedt, B. Adolph and W. G. Schmidt, "Ab Initio Calculation of Linear and Nonlinear Optical Properties of Semiconductor Structures",Braz. J. Phy., 1999,pp. 643-651.

[17] C. Y. Fong and Y. R. Shen, "Theoretical Studies on the Dispersion of the Nonlinear Optical Susceptibilities in GaAs, InAs and InSb", Phys. Rev. **B 12**, 1975, pp. 2325-2335.

[18] I. Vurgaftman, J. R. Meyer and L. R. Ram-Mohan , "Band Parameters for III-V Semiconductors and their alloys, J. Appl. Phys., 2001, pp.89.

[19] N. Nimje, S. Dubey, S. Ghosh, " Parametric Interaction in Acoustoptical Semiconductor Plasmas in the Presence of Hot-Carriers",Chin. J. Phys. **49,** 2011**.** pp.901-906 .

[20] A. K. Sundaram, P. K. Kaw and S. K. Sharma, "Kinetic Theory of Parametric Excitation of Acoustic Waves in Pizoelectric Semiconductors", Prama. **2,** 1974, pp.304-311 .

[21] K. P. Maheshwari and G. Tarey, " Resonant Excitation of Helicon waves by Two Microwave Beams in Solid State Plasma", Phys. Stat. Sol. (b) **133,** 1986, pp.417-421 **.**

[22] P. Aghamkar and P. K. Sen, " Parametric Excitation of Laser in Magnetoactive Doped Piezoelectric Semiconductors"Phys. Stat. Sol. (b) **156**, 1990, pp.735-743 .

[23] A. Neogi and S. Ghosh, J. Appl. Phys. **69**,1991, pp. 61.

[24] D. L. White, "Amplification of Ultrasonic Waves in Piezoelectric Semiconductors", J. Appl. Phys. **33**, 1962, pp. 2547.

[25] H. N. Spector, "Solid State Physics- Advances in Research and Application", Eds. F. Seitz and D. Turnbull, Academic Press, New York, 1966.

[26] P. K. Kaw, "Parametric Excitation of Ultrasonic Waves in Piezoelectric Semiconductors", J. Appl. Phys. **44**, 1973, pp. 1497.

[27] S. Guha, P. K. Sen and S. Ghosh, " Parametric Excitation of Acousto-Helicon Waves in Piezoelectric Semiconductors", Phys. Lett. **69 A**, 1978, pp.442-444.

[28] K. F. Lee, "Parametric excitation of upper hybrid and diffusion modes in a magnetized plasma", Phys. Lett. **A47**, 1974, pp. 257-258.

[29] V. S. Paverman and D. D. Tskhakaya, "Parametric interactions in Strontium Titanate Dielectric Microwave Resonators at 78 and 4.2 K", Fizika Astron. In Russ. 17, 1976, pp. 753-755.

[30] Yu. I. Balkarei and E. M. Epshtein, "Effect of Intense Electromagnetic Wave on the Propagation of Ultrasound in a Quantized Magnetic Field", JETP **36**, 1973, pp. 349.

[31] M. C. Steele and B. Vural, "Wave interaction in Solid State Plasmas", Mcgraw Hill, New York, 1969.

[32] S. Ghosh and V. K. Agrawal, " Parametrically Excited Instability of Hybrid Mode in Magnetised Semiconductors", Act. Phys. Polo. A **63**, 1983, pp.587-594.

[33] S. Guha and N. Apte, "Parametric Conversion of an Electron-Plasma Wave into an Electromagnetic Wave into Piezoelectric Semiconductor", J. Appl. Phys. **51**, 1980, pp. 5267-5272.

[34] S. Ghosh and V. K. Agarawal, "Parametric Decay of Laser Beam intoUltrasonic and Helicon Waves in Longitudinally Magnetised Semiconductors", Acustic A **52**, 1982, pp 31-35.

[35] A. A. Chaban, "Interaction of Intersecting Light Beams", Sov. Phys. JETP Lett **6**, 1968, pp. 1387-1391.

[36] R. B. Thompson and C. F. Quate, "Acoustic Parametric Oscillation in $LiNbO_3$ ", Appl. Phys. Lett. **16**, 1970, pp. 295-298.

[37] R. B. Thompson and C. F. Quate, " Nonlinear Interaction of Microwave Electric Fields and Sound in $LiNbO_3$ ", J. Appl. Phys. **42**, 1971, pp. 907-1013.

[38] N. Tozar, " Nonlinear Excitation of Density Fluctuations in Electron-Phonon system", Phys. Rev. **164**, 1967, pp. 518-522.

[39] S. Ghosh and R. B. Saxena, " Parametric Instabilities of Laser Beams in Material with Strain Dependent Dielectric Constant", Phys. Stat. Sol. (a) **96**, 1986, pp.111-119 .

[40] S. K. Sharms, J. Appl. Phys. **46**, 1975, pp.3712-3715.

[41] N. K. Ogg, " Acoustic Amplification in Materials in Strain –Dependent Dielectric Constants" , Phys. Lett. A **24**, 1967,pp. 472.

[42] C. L. Tang, W. R. Sosenberger, T. Ukachi, R. J. Lane and L. K. Chang, " Optical Parametric Oscillators ", Proc. IEEE **80**, 1992, pp. 365.

[43] S. Ghosh, G. Sharma and M. P. Rishi, " Diffusion Induced Parametric Amplification in Centrosymmetric Semiconductor Plasmas", Ind. J. Pure. And Appl. Phys. **40**, 2002, pp. 561-568.

[44] S. Ghosh, P. Thakur and N. Yadav , M. Jamil and M. Sallimullah, " Parametric Interactions In Ion-Implanted Piezoelectric Semiconductor Plasmas", Arab. J. Sc. Eng. **35**, 2010, pp. 231-240.

[45] S. Ghosh and P. Thakur, " Instability of Circularly Polarized Electrokinetic Waves in Magnetised Ion-Implanted Semiconductor Plasmas", Eur. Phys. J. D **31**, 2004, pp. 85.

[46] S. Ghosh, G. Sharma, P. Khare, M. Salimullah, " Modified Interactions of Longitudinal Plasmon-Phonon in Magnetised Piezoelectric Semiconductor Plasma", Physica B **351**, 2004, pp. 163.

[47] F. Haas, G. Manfredi, M. R. Feix, " A Multistream Model for Quantum Plasma", Phys. Rev. E **62,** 2000, pp. 2763-2783.

[48] F. Haas, L. G. Garcia, J. Goedert and G. Manfredi, " Quantum Ion-Acoustic Waves",Phys. Pla. **10,** 2003, pp. 3858-3867.

AUTHORS

First Author – Kirti Sontakke, Research Scholar, School of Studies in Physics, Vikram University Ujjain Madhya Pradesh 456010, India, email- kirtisontakke15@gmail.

Second Author – S. Ghosh, Professor and Head , School of Studies in Physics, email-drsanjayghoshssp@gmail.com

Correspondence Author – Kirti Sontakke , email- kirtisontakke15@gmail.com,,atulsontakke@maxlifeinsurance.com, mobile no.-9981255412, 9893812245, 0734-2517766.