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Possible lattice formation of new materials within a piezoelectric semiconductor plasma

M SALIMULLAH, S GHOSH* and M R AMIN
Department of Physics, Jahangirnagar University, Savar, Dhaka-1342, Bangladesh
*On Visiting Scientist Programme of the International Centre for Theoretical Physics, Trieste, Italy
*Permanent Address: School of Studies in Physics, Vikram University, Ujjain 456 010, India

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Abstract. The possible lattice formation of grains of chosen material in a magnetized current carrying n-type piezoelectric semiconductor plasma has been examined. In addition to the repulsive Coulomb potential, there appears a non-Coulombic oscillatory potential among the highly charged grains due to the strong resonant collective interaction of the grains and the electron-acoustic mode of the host semiconductor giving rise to the possibility of the lattice formation of grains of new materials.

Keywords. Coulomb crystal formation; magnetized piezoelectric semiconductor plasma; dust grains; electron-acoustic mode.

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Dusty plasmas are characterized as a low-temperature multi-species ionized gas comprising electrons, protons, and negatively (or positively) charged grains. In fact, the dust particles collect electrons and acquire an electric charge, which can be thousands of electron charges. The negative charging of grains could be due to field emission, plasma attachments, plasma currents, radiation field, etc. The grains can be trapped in the plasma, which floats positively with respect to the reactor walls. They not only interact with all the charge species through the Coulomb force but they respond to other forces also. The heavy mass of the particles and the strong spatial coupling make the system different from ordinary plasma systems but still make possible self organized collective phenomena. The importance of dusty plasmas has been recognized in the study of space environments such as asteroid zones, planetary rings, cometary tails, interstellar clouds, and Earth's noctilucent clouds. Dusty plasmas are found in low temperature radio-frequency and direct-current glow discharges, the plasma-aided manufacturing of semiconductors as well as near solid objects such as artificial satellites and the container-wall region of magnetically confined fusion plasmas. Ikezi [1] suggested the possibility for the charged dust particles to form a Coulomb solid if they are strongly coupled through the electrostatic force and have small thermal motion.

Recently, in view of demonstrating crystals of new material, direct observation of macroscopic Coulomb crystal formations and dust coagulation have been reported [2–8] in the strongly coupled dusty plasmas on the basis of theoretical prediction [1,9,10] of dust crystals and dust coagulation in laboratory and space plasma conditions. Low-frequency electrostatic fluctuations [3,4,11] as well as pairs of particulates with small separation have also been observed in addition to the formation of the macroscopic Coulomb crystals of solid particles and particle coagulation. A number of studies [12–15] have shown theoretically the particulate attraction to be operative due to the collective interaction of the charged particles with plasma modes of the dusty plasmas similar to the formation of Cooper pairs [16] in superconductors due to the presence of the electron plasma waves.

In this letter, we predict a novel possibility of the formation of Coulomb crystals of chosen material within a piezoelectric semiconductor where the plasma parameters can be varied over a wide range of values without much difficulties. When a given material, e.g. SiO_2, melamine, formaldehyde, etc. in the form of dust grains of a given size is released in a current-carrying piezoelectric semiconductor, e.g. n-InSb, the massive impurity grains may acquire a large charge on account of charging by electron sticking process (current) and thus a dusty plasma will be formed in the n-InSb crystal with the constituents of free electrons, floating highly-charged impurity grains in the static background of immobile positive lattice centres.

On account of the collective interaction of the impurity grains with internal modes of the semiconductor plasma, such as, an electron-acoustic mode, there appears an oscillating non-Coulombic attractive potential on the dust grains apart from the usual repulsive Coulomb potential between the grains of the same polarity.

Let us consider a dust-liberated n-type InSb sample in the presence of an external uniform magnetic field $\mathbf{B}_s \| \mathbf{z}$, through which a current is flowing, so that, the liberated grains acquire constant charge of large value compared to the charge of an electron. Thus, the multi-species semiconductor plasma with electrons, fixed ions and negatively charged floating dust grains will support the internal modes which can contribute to the attraction force between the dust particulates.

The dielectric response function of the piezoelectric semiconductor in the presence of the external static magnetic field and an electrostatic electron-acoustic mode is given by [17,18]

$$\epsilon(\mathbf{k},\omega) = \epsilon_L + \frac{i\omega_{\rm pe}^2}{\omega}\left[\frac{k_\perp^2(\nu_0 - i\omega + ik^2v_e^2/\omega)}{k^2\{\omega_{\rm ce}^2 + (\nu_0 - i\omega + ik^2v_e^2/\omega)\}} + \frac{k_{||}^2}{k^2(\nu_0 - i\omega + ik^2v_e^2/\omega)}\right] - \frac{K^2k^2c_s^2}{\omega^2 - k^2c_s^2}, \tag{1}$$

where ω is the wave frequency, $k_\perp(k_{||})$ is the component of the wave number $\mathbf{k}$ perpendicular(parallel) to $\mathbf{B}_s$, $\omega_{\rm ce}$ is the electron cyclotron frequency, $v_e = (2T_e/m_e)^{1/2}$ is the electron thermal velocity, c_s is the velocity of the ion-acoustic phonon, $\omega_{\rm pe} = (4\pi n_{e0}e^2/m_e)^{1/2}$ is the electron plasma frequency, ν_0 is the average electron-phonon collision frequency, ϵ_L is the lattice dielectric constant of the semiconductor under consideration and the last term of eq. (1) is the piezoelectric contribution from the lattice where K is the dimensionless electromechanical coupling coefficient [17,18]. The numerical value of K^2 for most of the piezoelectric semiconductors [19] is $\sim 10^{-3}$.

The electrostatic potential around an isolated test impurity (dust) grain in the presence of the electron-acoustic mode in the semiconductor dusty plasma can be written as [16,20]

$$\phi(\mathbf{r},\ t) = \frac{q_t}{2\pi^2}\int \frac{\delta(\omega - \mathbf{k}.\mathbf{v}_t)}{k^2\epsilon(\mathbf{k},\ \omega)}\exp[i\mathbf{k}.(\mathbf{r} - \mathbf{v}_t t)]\,\mathrm{d}\mathbf{k}\mathrm{d}\omega, \tag{2}$$

where q_t and v_t are the charge and velocity vectors, respectively.

We now consider two interesting cases of important parameter regime, which can be satisfied easily in piezoelectric semiconductors.

Case A: $\omega_{\rm pe}^2 > k^2 v_e^2 > \nu_0\omega$ and $k^2 v_e^2 > \omega_{\rm ce}\omega$

In this case the external magnetic field in the semiconductor dusty plasma may be ignored and the inverse of the real part of the plasma dielectric response function, $\epsilon(\mathbf{k},\ \omega)$ can be written in the following form:

$$\frac{1}{\epsilon_r(\mathbf{k},\ \omega)} = \frac{k^2\lambda_{\rm De}^2}{1+\epsilon_L k^2\lambda_{\rm De}^2}\left[1 + \frac{\omega_s^2}{\omega^2 - k^2 c_s^2 - \omega_s^2}\right], \tag{3}$$

where $\omega_s^2 = (K^2 k^4 v_e^2\lambda_{\rm De}^2)/(1+\epsilon_L k^2\lambda_{\rm De}^2)$, and $\lambda_{\rm De} = (T_e/4\pi n_{e0}e^2)^{1/2}$ is the electron Debye length.

Substituting eq. (3) in (2) and following the standard mathematical techniques [21, 12–15], we obtain the total electrostatic potential as the sum of the following two potentials

$$\phi = \phi_{\rm I} + \phi_{\rm II}, \tag{4}$$

where $\phi_{\rm I} = (q_t/r)\exp\left(-r/\sqrt{\epsilon_L}\lambda_{\rm De}\right)$ is the usual static Debye screening potential. If we use $(\rho,\ \theta,\ z)$ as the cylindrical coordinates of $\mathbf{r}$ where $r = [\rho^2 + (\xi + v_t t)^2]^{1/2}$ and $\xi = z - v_t t$, then $\phi_{\rm II}$, the additional potential involving the collective effects between the electron-acoustic wave and the test particulate is given by

$$\phi_{\rm II}(\rho,\ z,\ t) = \int \frac{q_t\lambda_{\rm De}^4 K^2 k^4 v_e^2}{\pi(1+\epsilon_L k^2\lambda_{\rm De}^2)} J_0(k_\perp\rho)\frac{\delta(\omega - k_\parallel v_t)}{\omega^2 - k^2 c_s^2} \exp(ik_\parallel\xi)k_\perp\,\mathrm{d}k_\perp\,\mathrm{d}k_\parallel\,\mathrm{d}\omega. \tag{5}$$

Evaluating the proper contour integration and k-integration from 0 to $k_e \equiv \lambda_{\rm De}^{-1}$ and with approximation $\epsilon_L k^2\lambda_{\rm De}^2 \ll 1$, we finally obtain

$$\phi_{\rm II}(\rho = 0,\ z,\ t) = \left(\frac{2q_t K^2 v_e^2}{c_s^2}\right)\frac{\cos(\xi/L_s)}{\xi}, \tag{6}$$

where $L_s = \lambda_{\rm De}(v_t^2 - c_s^2)^{1/2}/c_s$. Thus, we can obtain the ratio of the non-Coulombic oscillatory part of the wake potential to the usual positive Coulomb potential at a field point $(\rho = 0,\ z,\ t)$ as

$$\frac{\phi_{\rm II}}{\phi_{\rm I}} = 2K^2\left(\frac{v_e}{c_s}\right)^2\left(\frac{z}{\xi}\right)\exp[z/\sqrt{\epsilon_L}\lambda_{\rm De}]\cos(\xi/L_s). \tag{7}$$

It is noticed from eq. (6) that the oscillating wake potential is attractive when $\cos(\xi/L_s) < 0$ and the attractive potential can dominate over the repulsive Debye screened potential beyond the shielding cloud. The effective characteristic length L_s can be real positive only when $v_t > c_s$. Thus, the test particulates (dust grains) can attract each other forming a quasi-lattice structure within a piezoelectric semiconductor with the characteristic period of the order $L_s = \lambda_{\rm De}(v_t^2 - c_s^2)^{1/2}/c_s$.

Case B: $\omega_{\rm pe}^2 > k^2 v_e^2 > \nu_0\omega$ and $k^2 v_e^2 < \omega_{\rm ce}\omega$

In this limit, the dielectric response function reduces to

$$\epsilon(\mathbf{k},\ \omega) \cong \epsilon_L - \frac{\omega_{\rm pe}^2 v_e^2}{\omega_{\rm ce}^2 c_s^2} - \frac{K^2 k^2 c_s^2}{\omega^2 - k^2 c_s^2}. \tag{8}$$

The inverse of the dielectric response function can be written as

$$\frac{1}{\epsilon(\mathbf{k},\ \omega)} \cong \frac{1}{\epsilon_L - \omega_{\rm pe}^2 v_e^2/\omega_{\rm ce}^2 c_s^2}\left[1 + \frac{K^2 k^2 c_s^2/(\epsilon_L - \omega_{\rm pe}^2 v_e^2/\omega_{\rm ce}^2 c_s^2)}{\omega^2 - k^2 c_s^2}\right]. \tag{9}$$

Following the procedures of the previous section, we finally obtain at $(\rho = 0,\ z,\ t)$,

$$\frac{\phi_{\rm II}}{\phi_{\rm I}} = \frac{2K^2}{\epsilon_L - \omega_{\rm pe}^2 v_e^2/\omega_{\rm ce}^2 c_s^2}\cos(\xi/L_s). \tag{10}$$

Thus, in the case A, when $k^2 v_e^2 > \omega_{\rm ce}\omega$, the electron motion is independent of the external magnetic field. The non-Coulombic potential becomes oscillatory and the wake potential is attractive for some negative values of $\cos(|\xi|/L_s)$. By adjusting parameters we can show from eq. (7) that the attractive potential can dominate over the repulsive Coulomb potential. For the other case when $k^2 v_e^2 < \omega_{\rm ce}\omega$ with $\omega_{\rm pe}^2 > k^2 v_e^2 > \nu_0\omega$, the non-Coulombic potential is also oscillatory leading to attractive potential and the ratio of the non-Coulombic to Coulombic potentials is a sensitive function of plasma parameters (cf. eq. (9)). $|\ \phi_{\rm II}\ |$ can be much larger than $|\ \phi_{\rm I}\ |$ when $\omega_{\rm pe}^2 v_e^2/\omega_{\rm ce}^2 c_s^2 \cong \epsilon_L$.

In the conclusion, we have shown the possibility of attractive potential of a test impurity grain in a magnetized piezoelectric semiconductor whose constituents are the free electrons, floating highly charged dust grains in the background of fixed immobile positive lattice centres. Besides the usual repulsive Coulomb potential, there appears a non-Coulombic attractive potential. It may be mentioned here that if ω is close to kc_s, there appears a strong resonant interaction between the electron-acoustic mode and the test particle. When the latter moves with a velocity slightly larger than the phase velocity of the electron-acoustic wave in a piezoelectric semiconductor, then the potential behind the test particulate oscillates as a wake field, which serves the purpose of attracting particles of the same polarity. The test particulates can attract each other as well as the grains that are immersed in the background plasma. Hence, the formation of the quasi-lattice structures is, in principle, possible because of the periodic regions of attractive and repulsive forces between the particulates of the same polarity.

It may be mentioned here that the present theory provides a quantitative possibility for the attraction of the dust particulates in a magnetized piezoelectric semiconductor, which may become the cause for a possible grain crystallization. For quantitative comparison with results of the concrete experiments, other factors should be taken into account. In particular, the potential of ensemble (in contrast to the isolated test particle) of dust particulates might be calculated. This can be done by either adding the contributions of the isolated particulates (if their density is not high), or introducing their distribution function (when dust collective effects become important). Furthermore, contribution of total potential due to the ensemble of dust particulates as well as such factors as inhomogeneity of the grain distribution should be considered for the detailed picture. These are the subjects of future investigations. Some of them are underway now, and the results will be reported elsewhere.

It may further be added here that, although most of the piezoelectric semiconductors are opaque to visible and laser light, the possible formation of Coulomb crystalline structure of dust grains as in rf-produced laboratory plasmas [2–8], may be confirmed by x-ray or electron microscopic studies. Further, to a first approximation, the dust-phonon collision frequency may be considered very small compared to the electron-phonon collision frequency. Here, the mobility of the highly charged and massive dust-grains, $\mu_d \cong (q_d/m_d\nu_d)$ will take a finite value instead of apparent almost negligible mobility of a debris or a heavy impurity.

Thus for clear understanding of the dust-crystallization of new materials and for experimental verification of the results of our theoretical studies, we propose to initiate a series of laboratory experimental effort using a piezoelectric semiconductor (on account of their considerable ease of operation) where the parameters of the semiconductor could be varied over a wide range of values without much difficulty.

References

[1] H Ikezi, *Phys. Fluids* **29**, 1764 (1986)
[2] J H Chu and I Lin, *Phys. Rev. Lett.* **72**, 4009 (1994)
[3] J H Chu, J B Du and I Lin, *J. Phys.* **D27**, 296 (1994)
[4] H Thomas, G E Morfill, V Demmel, J Goree, B Feuerbacker and D Mohlmann, *Phys. Rev. Lett.* **73**, 652 (1994)
[5] Y Hayashi and K Tachibana, *Jap. J. Appl. Phys.* **33**, L804 (1994)
[6] A Melzer, T Trottenberg and A Piel, *Phys. Lett.* **A191**, 301 (1994)
[7] L Boufendi and A Bouchoule, *Plasma Sources Sci. Technol.* **3**, 262 (1994)
[8] M Shiratani, H Kawasaki, T Fukuzawa, H Tsuruoka, T Yoshioka and Y Watanabe, *Appl. Phys. Lett.* **65**, 1900 (1994)
[9] R T Farouki and S Hamaguchi, *Appl. Phys. Lett.* **61**, 1973 (1992)
[10] V N Tsytovich and O Havnes, *Comments Plasma Phys. Controlled Fusion* **15**, 267 (1993)
[11] R L Merlino, A Barkan, N D'Angelo, W Xu and B Song, in *AIP Conference Proceedings 345: International Conference on Plasma Physics 1CPP 1994, Foz do Iguacu, Brazil* edited by P H Sakanka and M Tendler (AIP Press, New York, 1995) pp. 295–302
[12] M Nambu, S V Vladimirov and P K Shukla, *Phys. Lett.* **A203**, 40 (1995)
[13] S V Vladimirov and M Nambu, *Phys. Rev.* **E52**, R2172 (1995)
[14] M Salimullah and M R Amin, *Phys. Plasmas* **3**, 1776 (1996)
[15] P K Shukla and M Salimullah, *Phys. Plasmas* **3**, 3858 (1996)
[16] P G de Gennes, *Superconductivity of metals and alloys* (Benjamin, New York, 1966) p. 102
[17] M C Steele and B Vural, *Wave interactions in solid state plasmas* (McGraw Hill, New York, 1969) p. 133
[18] M Salimullah, T Ferdousi and F Majid, *Phys. Rev.* **B50**, 141014 (1994)
[19] K Seegar, *Semiconductor Physics* (Springer-Verlag, Wein, 1973)
[20] N A Krall and A W Trivelpiece, *Principles of plasma physics* (McGraw Hill, New York, 1973) p. 562
[21] M Nambu and H Akama, *Phys. Fluids* **28**, 2300 (1985)