1. Introduction

The study of dust is important as its presence in astrophysical and space environment plays a vital role in different processes like mode modification. In laboratory plasma also, the presence of dust causes modifications in plasma processing [1–11]. The solitary waves are evolved as the result of the balance of nonlinearity and dispersion effects in the plasma [12]. The dust acoustic waves have been studied in a dusty plasma consisting of isothermal ions and electrons with Boltzmann distribution and dust grain with negative charge [9,13–15]. The presence of two-temperature ion plasma has attracted the researchers to explore more about it experimentally and theoretically [16,17]. Alm et al. have explored the presence of two-temperature ions in the magnetosphere [18]. The two ion temperature plasma present in Jovian magnetosphere, earth’s magnetotail and magnetosphere of asteroids and other planets provides opportunity to study nonlinear phenomena and explore space more and more [19]. People have largely discussed the ion-acoustic waves and solitons in dusty plasmas [3,20,21] and dust acoustic waves were explored least in most of the studies. Moreover, the dust temperature has been neglected and the dust was considered to be negatively charged [10,22–24]. For example, Malik et al. investigated solitons associated with negative potential in a plasma consisting of electrons, ions and dust grain, and analysed the impact of magnetic field strength [25]. Small amplitude solitons in magnetized dusty plasma have been investigated by Malik and Bharuthram for magnetized plasma where they have ignored the pressure gradient of the dust [24]. Lin and Duan studied magnetized two-ion temperature dusty plasma with dust size distribution using Zakharov-Kuznetsov equation [26]. Later Anowar and Mamun investigated the dust acoustic solitary waves in a plasma consisting of two-temperature ions and electrons following vortex-like distribution [27]. The study was later carried out by Emanuddin et al. for non-thermal ions and two-temperature non-extensive electrons carrying plasma, discussing the dust acoustic solitary waves [14]. Mishra and Wang discussed the presence of non-thermal electrons in magnetized dusty plasma and discussed the impact of the magnetic field and densities [28]. Srivastava et al. have studied four components plasma consisting of two-temperature ions, electrons and dust with a heavy charge for the homogeneous and inhomogeneous plasmas but with the neglect of magnetic field [29], which is essential to be considered when one talks about the space-related two-temperature ion plasmas. Shock waves have been studied in unmagnetized plasma with two-temperature ions in the magnetotail of earth by neglecting its magnetic effect [30]. The effect of magnetic field on solitons has been studied by Sharma et al., but they have considered only two-fluid plasma [31].

Keeping in mind, all the above points and the existence of two-temperature ion plasmas having dust in various situations, including the magnetosphere of the different celestial body, making the study more relevant for theoretical, experimental as well as laboratory research studies, we got inspired to study the dust acoustic waves and their evolution as solitons in such a plasma having dust grains of heavy charge and mass...
under the effect of the magnetic field. Especially the theoretical study is carried out in this paper to investigate the dust acoustic solitons in a magnetized dusty plasma consisting of inertialess electrons and two-temperature ions. The charge on dust grains is symbolized by $\mu$ (positive charge and negative charge are represented by $\mu^+ = 1$ and $\mu^- = -1$, respectively).

2. Basic equations

The proposed plasma model consists of finite-temperature electrons, two-temperature ions and dust grains bearing heavy charge and mass. The inertialess electrons, cold and hot ions have, respectively, the number densities $n_e, n_c, n_h$ and their corresponding temperature is represented as $T_e, T_c, T_h$. The mass of the dust grains is $m$, their temperature is $T$ and their number density is $n$. The charge on the dust grain is $\mu Z$, where $\mu$ represents the nature of the dust, means the dust is positively charged when $\mu = 1$ and it is negatively charged when $\mu = -1$. The magnetic field acting on the plasma is represented by $B_0$ acting along the $z$-axis, and the wave is considered to propagate in the $x-z$ plane at an angle $\theta$ with the direction of the magnetic field. The inertialess electrons and ions are assumed to follow Boltzmann distribution and the dust grains are defined by fluid dynamics using an equation of continuity and equation of motion. The basic equations for the said magnetized plasma are

$$
\begin{align*}
\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \vec{v}) &= 0, \\
\frac{\partial n_c}{\partial t} + \nabla \cdot (n_c \vec{v}) &= 0, \\
\frac{\partial n_h}{\partial t} + \nabla \cdot (n_h \vec{v}) &= 0,
\end{align*}
$$

\begin{align*}
\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} &= -\mu Z e\vec{v} + \mu Z e(\vec{v} \times \vec{B}) - \frac{2KT_d}{n} \nabla n,
\end{align*}

Here the velocity of the dust fluid is represented by $\vec{v}$ and $\phi$ represents the potential. For the study of nonlinear behaviour of the plasma, the reductive perturbation technique is employed to derive the relevant Korteweg-de Vries (KdV) equation. Normalization parameters are used in Equations (1)–(5) as used by Lakshmi and Bharuthram [9]. The normalization parameter for the dust velocity is the dust acoustic speed, given by $C_s = \sqrt{T_d/m}$, for the time it is the plasma oscillation frequency $\omega_p^2 = \sqrt{n_e Z e^2/4\pi m}$. For the spatial length, it is Debye length, given by $\lambda_D = (C_s/\omega_p)$, for the potential it is $T_d/Z e$, where $T_d = Z^2/n_0$ (Zeff/n_e + n_c/Te + n_h/Th), together with $n_0, n_c, n_h$ as the unperturbed number densities of the electrons, cold ions and hot ions, respectively, and $KT_d/T_{\text{eff}}$ is represented by $\sigma$. The number densities are normalized by $Z n_0$, where $n_0$ represents the equilibrium dust density. The normalized equations hence obtained are

$$
\begin{align*}
\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \vec{v}) + \frac{\partial (n_e \phi)}{\partial z} &= 0, \\
\frac{\partial n_c}{\partial t} + \nabla \cdot (n_c \vec{v}) + \frac{\partial (n_c \phi)}{\partial z} &= 0, \\
\frac{\partial n_h}{\partial t} + \nabla \cdot (n_h \vec{v}) + \frac{\partial (n_h \phi)}{\partial z} &= 0,
\end{align*}
$$

$$
\begin{align*}
n_e = n_0 e^{\phi/2KT_e}, \\
n_c = n_0 e^{-\phi/2KT_c}, \\
n_h = n_0 e^{-\phi/2KT_h},
\end{align*}
$$

$$
\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} + \nabla \phi &= -\mu Z e\vec{v} + \mu Z e(\vec{v} \times \vec{B}) - \frac{2KT_d}{n} \nabla n
$$

Equation (13) represents the normalized Poisson’s equation. Here $A = \frac{\vec{s}}{m}$ and $\Omega = \frac{B_0 z}{m}$. Furthermore, these normalized equations are treated with stretched coordinates $\xi$ and $\eta$, as

$$
\xi = \frac{1}{\sqrt{2}} (x \sin \theta + z \cos \theta - \lambda_0 t), \quad \eta = \frac{1}{\sqrt{2}} (x \sin \theta + z \cos \theta + \lambda_0 t).
$$

Here $\epsilon$ represents the small dimensionless expansion parameter. The phase velocity of the dust acoustic wave is represented by $\lambda_0$. For further investigation, the parameters like number densities, velocities and potential are expanded in terms of $\epsilon$ about their equilibrium values. The quantities after expansion take the following form:

$$
\begin{align*}
n &= \frac{1}{2} n_1 + \epsilon n_2 + \frac{\epsilon^2}{2} n_3 + \ldots, \\
\phi &= \frac{1}{2} \phi_1 + \epsilon \phi_2 + \frac{\epsilon^2}{2} \phi_3 + \ldots,
\end{align*}
$$

Here $n$ signifies $n, c, h$ and $\phi$ is $\phi, v$. In order to derive relevant KdV equation, the well-known reductive perturbation technique is used that includes the above expansions. Various equations are obtained at different orders of $\epsilon$. For example,

At the order of $\epsilon^{3/2}$,

$$
\begin{align*}
-\lambda_0 n_2 \xi &+ n_1 \xi + (\sin \theta / Z) v_2 \xi + (\cos \theta / Z) v_2 z \\
+ \cos \theta \phi_1 &+ n_1 v_2 \xi + \cos \phi_2 v_2 \xi = 0
\end{align*}
$$

$$
\begin{align*}
\phi_1 &- n_2 \xi + n_2 \xi + n_2 \xi = 0, \\
n_2 &= n_0 \phi \phi_2 T_e/(Z K T_e), \\
n_2 &= -n_0 \phi_2 T_e/(Z K T_e), \\
n_2 &= n_0 \phi_2 T_e/(Z K T_e),
\end{align*}
$$

$$
\begin{align*}
\lambda_0 v_2 z - \lambda_0 n_1 v_2 z &+ \frac{1}{2} v_2 z + \frac{\cos \theta \phi_1 v_2 z}{Z} \\
&+ \mu \cos \theta \phi_2, \\
\phi_2 &+ \cos \theta n_1 \phi_1 + \cos \phi_2 n_2 z = 0
\end{align*}
$$
\[-\frac{\lambda_0}{Z} \nu_{1\xi} + \frac{\mu AV_{2\xi}}{Z} = 0 \quad (20)\]

At the order of \(\varepsilon^{3/2}\),

\[v_{21} = \frac{n_1 \lambda_0}{\cos \theta}, \quad (21)\]

\[\phi_1 = \frac{(\lambda_0^2 - \cos^2 \theta 2\sigma) Z n_1}{\mu \cos^2 \theta} \quad (22)\]

\[v_{11} = \frac{Z}{\mu A} \left( \frac{\mu \sin \theta}{Z} \frac{\partial \phi_1}{\partial \xi} + \sin \theta 2\sigma \frac{\partial n_1}{\partial \xi} \right) \quad (23)\]

\[\lambda_0 = \cos^2 \theta \left( \frac{B_{11}^2 Z}{(\frac{\nu_{2\xi}}{kT_e} + \frac{\nu_{1\xi}}{kT_i} + \frac{\nu_{0\xi}}{B_0})} \right) + 2\sigma \quad (24)\]

Now the second-order quantities from Equations (14) –(20) are eliminated using first-order equations. Finally, the following KdV equation is obtained:

\[n_{1\eta} + \alpha n_1 n_{1\xi} + \beta n_{1\xi\xi} = 0 \quad (25)\]

where \(\alpha\) and \(\beta\) stand for the coefficients of nonlinearity and dispersion, respectively:

\[\alpha = \frac{3\lambda_0^2 Z - 2\sigma Z \cos^2 \theta}{2\lambda_0} \quad (25)\]

\[\beta = \frac{[A^2 (\lambda_0^2 - 2\sigma \cos^2 \theta)^2 + \lambda_0^4 \sin^2 \theta]}{2\lambda_0 \mu^2 A^2 \cos^2 \theta} \quad (26)\]

To obtain the solution of the KdV equation, the above equation is converted into a single variable differential equation in \(\tau\). The transformation for the above requirement is \(\tau = \xi - U_0\), where \(U_0\) is a constant velocity. This equation is then integrated for the boundary conditions that \(n_1\) and all its derivatives with respect to \(\tau\) vanish when \(|\tau| \to \pm \infty\). The solution thus obtained is

\[n_1(\tau) = n_m \sec h^2 (\tau/W) \quad (27)\]

Here \(n_m = 3U/\alpha\) represents the amplitude of the soliton and \(W = 2\sqrt{\beta/\alpha}\) represents the width of the soliton. In order to evaluate the solitons’ characteristics, the expressions of \(\alpha\) and \(\beta\) are employed from Equations (25) and (26).

### 3. Results and discussion

The analysis of dust acoustic wave and its evolution in soliton in magnetized dusty two-ion temperature plasma is discussed using the space-related parameters. For example, electron number density is taken as \(n_{e0} = 10^{17}m^{-3}\), cold ion number density is taken as \(n_{i0} = 10^{13}m^{-3}\), and hot ion number density is taken as \(n_{h0} = 10^4\) times \(n_{i0}\). The dust number density is calculated using quasi-neutrality condition \(n_0 = (n_{e0} - n_{h0} - n_{i0})/\mu Z\). The charge on the dust is taken as \(Z = 1000\) (unless stated), the mass of the dust is taken as \(m = 10^{-22}\) kg, the temperature of the dust is taken as \(KT_d = 0.01eV\), the electron temperature is taken as \(KT_e = 5eV\), the cold ion temperature is taken as \(KT_c = 0.1eV\), the hot ion temperature is taken as \(KT_h = 1eV\), the magnetic field is taken as \(B_0 = 10^{-3}\) Tesla and the angle of propagation of the wave is taken as \(\theta = 30^\circ\) [25,32,33].

The results on the nonlinear behaviour of the dust acoustic wave are discussed. The results obtained here show the interesting impact of the number density and temperature of hot ions, cold ion number density, dust temperature, dust charge, mass of the dust and angle of wave propagation. The impact of these parameters on the soliton’s amplitude and width in graphical form is presented along with an analysis based on the percentage change in the soliton’s characteristics. Figure 1 shows the modification in soliton structure when the dust temperature and hot ion temperature are varied. The dust temperature and the hot ion temperature are found to affect the solitons inversely. For example, the increase in hot ion temperature decreases the amplitude of the soliton; for an increase in hot ion temperature by three times the soliton amplitude falls by 4%, whereas the amplitude increases by 16.67% when the dust temperature is increased by five times. This variation can be explained in terms of the restoring force which arises during the oscillations of the dust grains and the ions. Since the wave acquires inertia due to the dust mass, the impact of the dust temperature or the thermal effects is more than that of the ion temperature. Similar results but more significant changes are observed in Figure 2, where the dust charge is taken as 500 in place of 1000, means it is half of that taken in Figure 1. Here, for the same variation of the hot ion temperature, as in Figure 1, the fall in the soliton amplitude is 9.09% (which is more than double as of the previous case). The dust temperature also plays a dominating role in view of the fact that the peak amplitude of the soliton is increased by 44% for the same variation of

![Figure 1](https://example.com/fig1.png)

**Figure 1.** Modification of soliton structure in the magnetized plasma with the variation of hot ion temperature \(KT_h\) and dust temperature \(KT_d\), when \(Z = 1000\), \(KT_c = 0.1eV\), \(KT_e = 5eV\), \(n_{e0} = 10^{17}m^{-3}\), \(n_{i0} = 10^{13}m^{-3}\), \(n_{h0} = 10000 \times n_{i0}\), \(\theta = 30^\circ\), \(B_0 = 10^{-3}\) Tesla, \(v_0 = 10^{-1}\) C, and \(U = 1\).
H. K. MALIK ET AL.

Figure 2. Modification of soliton structure in the magnetized plasma with the variation of hot ion temperature $K_{T_h}$ and dust ion temperature $K_{T_d}$, when $Z = 500$ and the rest of the parameters are the same as in Figure 1.

dust temperature. This is clear from these two figures that the impact of dust charge decreases the amplitude of the soliton. If all the other parameters are kept constant, there is a remarkable difference in the amplitude and width of the soliton for the variation of dust temperature and charge.

The effect of $Z$ is further investigated in Figure 3 for the magnetized dusty plasma as well as the electron-depleted magnetized dusty plasma ($n_{e0} = 0$). The electron-depleted plasma consists of a sufficiently low density of electrons, as most of the electrons are absorbed by the dust. The dust charge contributes more towards increasing the width of the soliton, whereas enhancement in the charge decreases the amplitude of the soliton, which signifies that the more negative charge on the dust increases ambipolar diffusion in the plasma. The role of dust charge for the electron-depleted plasma is clear from Figure 3 where the soliton of smaller size is evolved. Here also the amplitude is decreased by 13.64% and the width is increased by 75% for the enhancement of dust charge from 800 to 1000. A similar observation is carried out for the impact of the angle of wave propagation through Figure 4. The increase in the angle of the propagation of the wave increases the amplitude of the soliton heavily, whereas the amplitude decreases for the electron-depleted plasma and the width of the soliton increases. This difference is made by the absence of the electrons and hence the reduced restoring force in the electron-depleted plasma. This is in view of the fact that the dust density also reduces for the fixed densities of the hot and cold ions and the reduced density of the electrons.

For the electron-depleted plasma, the mass of the dust plays a significant role and the increase in the mass increases the width of the soliton in Figure 5. This is due to the fact that the wave acquires lower frequency in view of the reduced cyclotron frequency of the dust grains and the reduced restoring force; finally, it sees a less dispersive effect in the plasma. Other investigators have also realized for the ion-acoustic solitons that the magnetic field modifies the dispersive property of

Figure 3. Modification of soliton structure in the magnetized plasma and electron-depleted magnetized plasma ($n_{e0} = 0$) with the variation of charge on the dust $Z$, when the other parameters are the same as in Figure 1.

Figure 4. Modification of soliton structure in the magnetized plasma and electron-depleted plasma ($n_{e0} = 0$) with the variation of the angle of propagation of mode ($\theta$), when the other parameters are the same as in Figure 1.

Figure 5. Variation in soliton structure in the magnetized electron-depleted plasma ($n_{e0} = 0$) with the dust mass when the other parameters are the same as in Figure 1.
the plasma and only the soliton width is affected by this external magnetic field [6,24]. On the other hand, the role of the dust mass is found to be insignificant (Figure not shown) when there is a sufficient number of electrons in the plasma.

The plasma parameters used in the present manuscript correspond to the plasmas present in Jovian magnetosphere, earth’s magnetotail, the magnetosphere of asteroids or other planets. Hence, the application of the findings will be in nonlinear phenomena realized in such plasmas. Another interesting application of the findings will be in plasma processing, where dust is generated and also the ions may attain two temperatures in view of the use of magnetic field and negative biases [34,35].

4. Conclusions

The dust acoustic soliton evolution in the magnetized dusty plasma for massive and negatively or positively charged dust grains is investigated and a comparative effect is observed in the electron-depleted plasma also. The effect of hot ions is found to be significant when their number is very high as compared to the number of cold ions. The dust charge and its mass decrease the amplitude of the soliton. The presence of more electrons in the plasma increases the amplitude of the soliton. The angle of the wave propagation affects the soliton in a positive manner and the amplitude of the soliton increases when the wave propagates at a larger angle to the direction of the magnetic field.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Hitendra K. Malik  http://orcid.org/0000-0002-9432-8140
Rashmi Srivastava  http://orcid.org/0000-0002-0415-5486
Sandeep Kumar  http://orcid.org/0000-0003-1681-7085
Devi Singh  http://orcid.org/0000-0002-6345-5550

References

[1] Malik HK, Singh DK, Nishida Y. On reflection of solitary waves in a magnetized multicomponent plasma with nonisothermal electrons. Phys Plasmas. 2009;16:072112.
[2] Abdo NF. Effect of non Maxwellian distribution on the dressed electrostatic wave and energy properties. J Taibah Univ Sci. 2017;11:617–622.
[3] El-Shewy EK, Abdelwahed HG, Abdo NF, et al. On the modulation of ionic velocity in electron–positron–ion plasmas. J Taibah Univ Sci. 2017;11:1267–1274.
[4] Farooq M, Ahmad M. Dust ion acoustic waves in four component magnetized dusty plasma with effect of slow rotation and superthermal electrons. Phys Plasmas. 2017;24.
[5] Nishida Y, Nagasawa T. Excitation of ion-acoustic rarefactive solitons in a two-electron-temperature plasma. Phys Fluids. 1986;29:345.
[6] Malik HK. Ion acoustic solitons in a weakly relativistic magnetized warm plasma. Phys Rev E. 1996;54:5844.
[7] Singh SV, Rao NN. Linear and nonlinear dust-acoustic waves in inhomogeneous dusty plasmas. Phys Plasmas. 1998;5:94–99.
[8] Malik HK, Dahiya RP. Ion acoustic solitons in finite ion temperature inhomogeneous plasmas having negative ions. Phys Plasmas. 1994;1:2872–2875.
[9] Lakshmi SV, Bharuthram R. Arbitrary amplitude rarefactive dust-acoustic solitons. Planet Space Sci. 1994;42:875–881.
[10] Sharif Moghadam S, Dorranian D. Effect of size distribution on the dust acoustic solitary waves in dusty plasma with two kinds of nonthermal ions. Adv Mater Sci Eng. 2013;2013:1–6.
[11] Dorranian D, Sabetkar A. Dust acoustic solitary waves in a dusty plasma with two kinds of nonthermal ions at different temperatures. Phys Plasmas. 2012;19:013702.
[12] Merlino RL. 25 years of dust acoustic waves. J Plasma Phys. 2014;80:773–786.
[13] Rao NN, Shukla PK, Yu MY. Dust-acoustic waves in dusty plasmas. Planet Space Sci. 1990;38:543–546.
[14] Emamuddin M, Masud MM, Mamun AA. Dust-acoustic solitary waves in a magnetized dusty plasma with non-thermal ions and two-temperature nonextensive electrons. Astrophys Space Sci. 2014;349:821–828.
[15] Malik R, Malik HK. Compressive solitons in a moving e-p plasma under the effect of dust grains and an external magnetic field. J Theor Appl Phys. 2013;7:65.
[16] Balsiger H, Altwegg K, Bühler F, et al. Ion composition and dynamics at comet Halley. Nature. 1986;321:330–334.
[17] Kikuchi H, ed. Dusty and dirty plasmas, noise, and chaos in space and in the laboratory. Boston (MA): Springer US; 1994.
[18] Alm L, André M, Vaivads A, et al. Magnetotail Hall Physics in the presence of Cold Ions. Geophys Res Lett. 2018;45(20):10941–10950. doi:10.1029/2018GL079857.
[19] Hellberg MA, Verheest F. Ion-acoustic solitons in plasmas with two-temperature ions. Phys Plasmas. 2008;15:062307.
[20] Tomar R, Malik HK, Dahiya RP. Reflection of ion acoustic solitary waves in a dusty plasma with variable charge dust. J Theor Appl Phys. 2014;8(126). doi:10.1007/s40094-014-0126-8.
[21] El-Hanbaly AM, El-Shewy EK, Sallah M, et al. Linear and nonlinear analysis of dust acoustic waves in dissipative space dusty plasmas with trapped ions. J Theor Appl Phys. 2015;9:167–176.
[22] Tyagi J, Singh S, Malik HK. Effect of dust on tilted electrostatic resistive instability in a Hall thruster. J Theor Appl Phys. 2018;12:39–43.
[23] Asaduzzaman M, Mamun AA. Effects of nonthermal ions and polarization force on dust-acoustic waves in a density-varying dusty plasma. Phys Rev E. 2012;86:1.
[24] Malik HK, Bharuthram R. Small amplitude solitons in a magnetized dusty plasma with two-ion species. Phys Plasmas. 1998;5:3560–3564.
[25] Malik HK, Tripathi KD, Sharma SK. Dust acoustic solitons in a magnetized dusty plasma. J Plasma Phys. 1998;60:265–273.
[26] Lin M, Duan W. Nonlinear dust acoustic waves in magnetized two-ion-temperature dusty plasmas. Phys Plasmas. 2004;11:5710–5715.
[27] Anowar MGM, Mamun AA. Effects of two-temperature electrons and trapped ions on multidimensional instability of dust-acoustic solitary waves. IEEE Trans Plasma Sci. 2009;37:1638–1645.
[28] Misra AP, Wang Y. Dust-acoustic solitary waves in a magnetized dusty plasma with nonthermal electrons and trapped ions. Commun Nonlinear Sci Numer Simul. 2015;22:1360–1369.

[29] Srivastava R, Malik HK, Singh D. Comparative study of dust acoustic solitons in two-temperature ion homogeneous and inhomogeneous plasmas. J Theor Appl Phys. 2020;14:11–20. doi:10.1007/s40094-019-00365-1.

[30] Ghai Y, Saini NS. Shock waves in dusty plasma with two temperature superthermal ions. Astrophys Space Sci. 2017;362(58). doi:10.1007/s10509-017-3037-8.

[31] Sharma A, Malik HK, Kumar H, et al. Effect of magnetic field on electromagnetic soliton evolution by different pulses. J Theor Appl Phys. 2019;13:31–37.

[32] Asgari H, Muniandy SV, Wong CS. Dust-acoustic solitary waves in dusty plasmas with non-thermal ions. Phys Plasmas. 2013;20:023705.

[33] Shukla PK, Eliasson B. Stimulated scattering of electromagnetic waves carrying orbital angular momentum in quantum plasmas. Phys Rev E. 2012;86:016403.

[34] Singh O, Malik HK, Dahiya RP, et al. Tuning of mechanical and structural properties of 20 MC 5 steel using N ion implantation and subsequent annealing. J Alloys Compd. 2017;710:253–259.

[35] Jangir SK, Malik HK, Saho P, et al. Electrical transport and gas sensing characteristics of dielectrophoretically aligned MBE grown catalyst free InAs nanowires. Nanotechnology. 2019;30:105706.