## THE EFFECT OF A HIGH-FREQUENCY ELECTROMAGNETIC FIELD ON THE BREATHER-ELECTRIC EFFECT IN A NON-ADDITIVE SUPERLATTICE

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### I. INTRODUCTION

Superlattices (SL) are still of interest to researchers for several reasons. One of them is the possibility of propagation of nonlinear electromagnetic waves at relatively small field strengths (about $10^3$ V / cm) [1-4]. In this case, the propagation of electromagnetic waves in the superlattice is described by the sine-Gordon equation, which also describes a few physical phenomena in various systems [5].

The effect of charge entrainment by a breather in superlattices with a model spectrum in the strong coupling approximation in the presence of a warming electromagnetic field is investigated.

### II. MAIN PART

Let us consider an SL that is periodical along the Oz axis. The dispersion law for this SL has the form ($\hbar = 1$)

$$\varepsilon(\boldsymbol{p}) = \varepsilon(\boldsymbol{p}_\perp) + \Delta(1-\cos(p_z d)) \quad (1)$$

where d is the superlattice period, Δ is the half-width of the conduction miniband. In this case, the form of the transverse part of the energy spectrum $\varepsilon(\boldsymbol{p}_\perp)$ depends on the material on the basis of which the superlattice is made. For GaAs / AlGaAs-based superlattices $\varepsilon(\boldsymbol{p}_\perp) = \frac{\boldsymbol{p}_\perp^2}{2m}$. For graphene-based superlattices $\varepsilon(\boldsymbol{p}_\perp) = \sqrt{\Delta_1^2 + v_F^2 p_z^2}$.

The propagation of short electromagnetic pulses in an SL along its layers in the collisionless approximation is described by the sine-Gordon equation

$$\frac{\partial^2\varphi}{\partial\tau^2} - \frac{\partial^2\varphi}{\partial\chi^2} + \sin(\varphi) = 0 \quad (2)$$

where $\chi = \frac{\omega_{pl} z}{c}$ – is the dimensionless coordinate, $\tau = \omega_{pl} t$ – is the dimensionless time, $\varphi = \frac{edA}{\hbar c}$ - is the dimensionless vector potential of the pulse electromagnetic field associated with the electric field strength $E(t)$ by the relation $\varphi = ed\int_{-\infty}^{t} E(t')\,dt'$, $\omega_{pl} = \frac{2\pi ed}{\hbar\sqrt{\frac{2n\Delta I_1(\theta)}{I_0(\theta)}}}$ is the plasma frequency of electrons in the conduction miniband, *n* – is the concentration charge carriers in the SL, *c* – is the rate of electromagnetic radiation in vacuum, $I_1(\theta), I_0(\theta)$ – are the modified Bessel functions, $\theta$ – is the temperature in energy units.

Some of the simplest and most studied solutions of equation (2) are the so-called *N*-soliton solutions [6]. However, this equation also has more complex solutions. In addition to soliton solutions, a doublet solution stands out, otherwise called a bion or breather (the term “breathing” solution is also encountered). The possibility of propagation of electromagnetic breathers in a semiconductor superlattice was demonstrated in [7]. Mathematically, the doublet solution looks like this (in dimensional coordinates):

$$\varphi(y,t) = 4arctg\left(\alpha\frac{sin\left(\omega^*\left(t-\frac{uy}{c^2}\right)\right)}{ch\left(\omega_1^*\left(t-\frac{y}{u}\right)\right)}\right)$$

where $\alpha = \frac{\omega_1}{\omega}$, $\omega_1 = \sqrt{\omega_{pl}^2 - \omega^2}$, $\beta = \frac{u}{c}$, $\gamma = (1-\beta^2)^{-\frac{1}{2}}$, $\omega^* = \gamma\omega$, $\omega_1 = \gamma\beta\omega$.

Physically, the doublet solution can be interpreted as a coupled (oscillating with frequency $\omega$) state of a soliton-antisoliton pair.

For the experimental detection of breathers in superlattices, the effect of dragging electrons by them (breather-electric effect) can be used. A similar effect is also observed in the case of propagation of solitons (solitonoelectric effect).

It was shown in [6] that in the case of application of a high-frequency field with an intensity along the SL axis, equation (2) is modified as follows [8]

$$\frac{\partial^2\varphi}{\partial\tau^2} - \frac{\partial^2\varphi}{\partial\chi^2} + J_0(a)\sin(\varphi) = 0 \tag{3}$$

where $a = eEd\,/\omega$.

We will assume that the width of a solitary wave is large in comparison with the mean free path of an electron, and the time of action of a solitary wave on an electron is small in comparison with the time of free path of an electron; at typical values of the parameters, these assumptions are fulfilled. Under these conditions, we obtain an expression for the drag current density, determined by the following formula:

$$j(\tau) = \frac{4n_0\Delta e}{mV}\int_{-\infty}^{t} F(\tau_1)\sin\big(\varphi(\tau_1)\big)\,d\tau_1 \tag{4}$$

where

$$F(\tau) = \widetilde{\omega}^*\tilde{\alpha}\frac{\tilde{\alpha}\sin(\widetilde{\omega}^*\tau)\,sh(\widetilde{\omega}_1^*\tau) - \beta\cos(\widetilde{\omega}^*\tau)\,ch(\widetilde{\omega}_1^*\tau)}{ch^2(\widetilde{\omega}_1^*\tau) + \tilde{\alpha}^2\sin^2(\widetilde{\omega}^*\tau)} \tag{5}$$

$$\tilde{\alpha} = \sqrt{J_0(a)\omega_{pl}^2/\omega^2 - 1},\, \widetilde{\omega}^* = \frac{\gamma\omega}{\omega_{pl}},\, \widetilde{\omega}_1^* = \gamma\beta\sqrt{J_0(a) - \omega^2/\omega_{pl}^2}$$

To find the transferred charge (namely, it is detected experimentally), it is necessary to integrate expression (5) from minus to plus infinity. In the case of $\alpha \ll 1$ this can be done analytically, but in the general case of an arbitrary bond strength, the study can only be carried out numerically. Let us immediately note the main feature in expression (5) - for a certain value of the dimensionless strength of the high-frequency field *a*, the value of $\tilde{\alpha}$ can become complex, since in the expression under the root $J_0(a)\omega_{pl}^2/\omega^2 - 1$ the first term decreases with increasing *a*. We can say that at this point the breather solution loses its stability and the breather-electric effect disappears. Earlier in [7], it was noted that when considering the soliton-electric effect under the conditions of an alternating field, a similar effect occurs - the soliton solution loses its stability at a field value for which $J_0(a) = 0$. However, this condition has a simple physical interpretation: the high-frequency field heats up the electron gas and at $J_0(a) = 0$ the average energy becomes greater than the half-width of the conduction miniband, and the propagation of amplified pulses becomes possible - an autosoliton solution. In the case of a breather solution, it loses stability even before the distribution of electrons is inverted; therefore, the physical reason for the loss of stability is still unclear and the issue requires additional research.

III. CONCLUSIONS

The paper investigates the propagation of the breather of the sine-Gordon equation under the influence of a high-frequency field. The features of the entrainment of the charge by such a pulse are noted.

REFERENCES

[1] E.M.Epshtein, “Drag of Electrons by Solitons in Semiconductor Superlattice,” Sov.Phys.Solid State. 14(12), 2422 (1980) [in Russian].

[2] F.G. Bass and A.A. Bulgakov, *Kinetic and Electro- dynamic Phenomena in Classical and Quantum Semiconductor Superlattices* (Nova Science Publ., N.Y., 1997).

[3] S.Y.Mensah, F.K.A. Allotey, and N.G.Mensah, “Excitation of Breather (Bion) in Superlattice,” Phys. Scripta. 62, 212 (2000).

[4] S.V.Kryuchkov and E.I.Kukhar', "TheSolitaryElec- tromagnetic Waves in the Graphene Superlattice" Physica B. 408, 188 (2013).

[5] K. Lonngren and A. Scott, Solitons in Action (Aca- demic Press, N.Y., 1978).

[6] J. L. Lamb. Elements of soliton theory / J. L. Lamb (New York etc., 1980).

[7] S.V. Kryuchkov and G.A. Syrodoev, 1990, Fiz. Tekh. Poluprovodn. (Leningrad), 24, no. 6, 1120.

[8] S. V. Kryuchkov and E. I. Kukhar', «Possibility of Propagation of Dissipative Solitons in AC-Driven Superlattice», Physics of Wave Phenomena, 2015, Vol. 23, No. 1, pp. 21–27.