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Stochastic resonance as a defect transformation mechanism in III-V semiconductor compounds under the action of electromagnetic and pulsed magnetic fields

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Abstract. The phenomenon of stochastic resonance of defects in III-V semiconductor compounds under the action of microwave radiation and pulsed magnetic fields has been discussed. The features of the resonant transformation of particle ensembles obeying statistical laws have been studied. The results have been applied to substantiate the observed changes in the surface morphology of III-V semiconductor compounds after pulsed magnetic field treatment. An estimation of the frequency of stochastic resonance has been provided.

Keywords: semiconductor, defect, microwave radiation, magnetic field, stochastic resonance.

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1. Introduction

Non-thermal effects of microwave radiation have been observed during irradiation of various substances: bacterial systems [1, 2], organic compounds [3, 4], and solids [5–8]. The proposed mechanisms of these effects are often either phenomenological in nature [3] (which complicates their practical application) or concern only ionic crystals [5]. Resonance mechanisms of defect structure transformation are universal for semiconductor materials [7, 8]. The concepts of resonance phenomena may be used to analyze the defect transformations in III-V semiconductor structures both under non-thermal action of microwave radiation [8] and during pulsed magnetic fields treatment [9].

By its nature, electrical resonance refers to phenomena that describe deterministic patterns of behavior (oscillations) of a certain point or a linear charged defect. At the same time, semiconductor crystals contain a large number of defects that are under the influence of fluctuation forces of a thermal nature and thus obey the statistical laws. Therefore, the entire set of defects in a semiconductor crystal form a statistical ensemble of defects, the behavior of which must also obey statistical laws. It may be assumed that this feature can effect on the specifics of resonance phenomena in semiconductor structures under the action of electromagnetic and magnetic fields.

The present paper aims at providing an analysis of resonance behavior of point defects obeying statistical laws, in III-V semiconductor compounds under the action of microwave radiation and pulsed magnetic fields.

2. Stochastic resonance of point defects in semiconductor compounds

Let us analyze the dynamics of point defects, namely impurity atoms and ions (hereinafter referred to as particles), under the action of microwave radiation and pulsed magnetic field. In the initial state, the particles are situated in local minima $\pm x_m$ of double potential wells separated by a potential barrier V_0 (Fig. 1).

For III-V compounds, covalent chemical bonds are formed through a donor-acceptor (coordination) mechanism. Of the four covalent bonds, by which each atom is built into the lattice, three atoms are bonded by the shared valence electrons of atoms A and B, while the fourth bond is created by the unshared pair of valence electrons of atoms B (donor) and the free orbital of atoms A (acceptor). In each covalent bond, the maximum of the electron density is shifted towards the atom with greater electronegativity, *i.e.* to the atom B. As a result, the atoms A acquire an effective positive charge, and the atoms B – a negative charge. Hence, the chemical bond is covalent with a certain degree of ionicity (the so-called covalent polar bond).

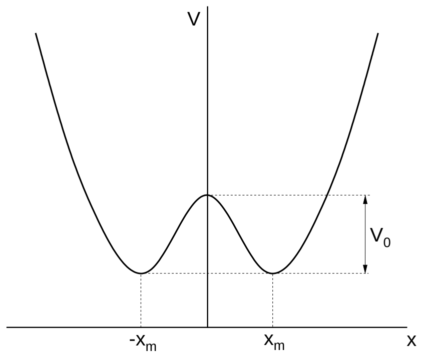

Fig. 1. Schematic representation of local minima of a double potential well for the initial state of a particle.

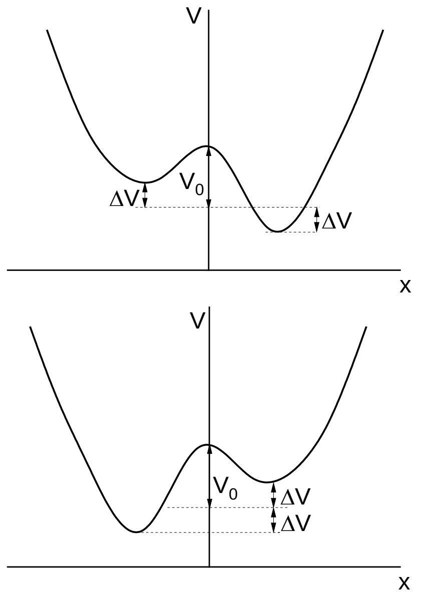

Fig. 2. Deformed potential of a double well due to external influence.

When a semiconductor structure is exposed to microwave radiation, periodic electric component of the electromagnetic field with the frequency ω interacts with the effective charges of atoms A and B with a force equal to $A_0 \cos(\omega t + \varphi)$, where $A_0 = QE_0$ is the amplitude of the electric force, E_0 is the amplitude of the strength of the electric component of electromagnetic oscillations, and Q is the parameter with the dimension of a charge, characterizing the degree of polarity (ionicity) of the chemical bond. As a result of this interaction, the double-well potential is deformed, *i.e.* it periodically changes the height of the potential barriers of the right and left wells in an antisymmetric manner by the value $\Delta V(\omega) = \pm x_m A_0 \cos(\omega t + \varphi)$ (Fig. 2). The maximum (amplitude) value of ΔV is $\Delta V_{\max} = x_m A_0$.

It may be assumed that a similar process is observed when a semiconductor crystal is exposed to a pulsed magnetic field. Indeed, calculations show that in a magnetic field, mobile charge carriers in a semiconductor are a source of electromagnetic radiation at a cyclotron frequency [7, 9, 10].

At small amplitudes of the electrical component of electromagnetic oscillations, the change in the potential barrier height is small ($\Delta V < V_0$), and, therefore, is insufficient for the particle to overcome the potential barrier and move from one local minimum to another.

The picture considered changes radically if it is supplemented by the important circumstance that the particles in a symmetric double well are subject to thermal fluctuations. Mathematically, the thermal fluctuations may be interpreted as white noise $\xi(t)$ with a Gaussian distribution around a zero mean value and an autocorrelation function $\langle \xi(t)\xi(0) \rangle$ in the following form [11, 12]:

$$\langle \xi(t)\xi(0) \rangle = 2D\delta(t), \tag{1}$$

where $\delta(t)$ is the Dirac delta function, D is the noise intensity (dispersion of the distribution, $D = kT$), k is the Boltzmann constant, and T is the absolute temperature, respectively. In the absence of a periodic electrical action, the particle oscillates around its local equilibrium state with a statistical dispersion proportional to the noise intensity D. These thermal fluctuations cause particle jumps between adjacent local minima of the potential well. The frequency of the particle jumps f_k under the action of a noise $\xi(t)$ is [12]:

$$f_k = \nu_0 \exp\left(-\frac{V_0}{D}\right), \tag{2}$$

where ν_0 is the frequency factor, which by the order of magnitude coincides with the frequency of thermal (noise) oscillations of the particle ($\nu_0 = D/2\pi\eta$, where $\hbar$ is the Planck constant). At T = 298 K, we have $\nu_0 = 6.2 \cdot 10^{12}$ Hz.

Under certain conditions, this noise can lead to a significant increase in the ion response to the action of even small periodically changing electrical forces.

Let us consider the change in the coordinate $x(t)$ of a particle with the mass m in a symmetric double potential well under the action of a periodically changing electrical force and white noise. The particle motion obeys the Langevin equation [11]:

$$m\frac{d^2x}{dt^2} = m\gamma\frac{dx}{dt} - \frac{dV(x)}{dt} + mA_0 \cos(\omega t + \varphi) + \sqrt{2m\gamma D}\,\xi(t), \tag{3}$$

where $V(x) = -(a/2)x^2 + (b/4)x^4$ is the potential energy of a symmetric double well (a and b are the potential parameters) and γ is the attenuation (dissipation) coefficient.

At strong attenuation and a small amplitude of the electric force, the value of the particle position averaged over the ensemble of noise realizations $\overline{x(t)}$ has the following form [11]:

$$\overline{x(t)} = \overline{x(D)}\cos\left(\omega t - \overline{\psi}\right), \tag{4}$$

where $\overline{x(D)}$ is the amplitude of the particle displacement and $\overline{\psi}$ is the phase.

For $\overline{x(D)}$, the following approximate relation holds [11]:

$$\overline{x(D)} = \frac{A_0 x_m^2}{D} \frac{2 f_k}{\sqrt{4 f_k^2 + \omega^2}}. \tag{5}$$

It follows from (5) and (2) that the amplitude $\overline{x(D)}$ depends non-monotonically on the noise intensity *D*. First, the amplitude value increases with increase in *D*, reaches a maximum and then decreases again [11]. This phenomenon is called stochastic resonance [11, 12]. It consists in the following. Despite the fact that the periodic action (in our case, of electrical nature) is too weak to allow the particle to periodically roll from one local minimum to another, nevertheless, the noise-induced jumps between the potential wells can become synchronized with the weak periodic action.

This statistical synchronization consists in the fact that the jumps between the minima of a symmetric double potential well, stimulated by noise, occur at the frequency of the weak periodic action at the moments of peak values of the latter. In fact, such a resonant response of a dynamic system to a weak periodic action is a consequence of a synchronized transfer of the noise energy into the energy of the periodic action [13].

Statistical synchronization occurs when the average waiting time for a noise-induced transition between two potential wells, $T_k(D) = 1/f_k$, is equal to half the period of oscillations of the periodic electric force $T_\omega = 2\pi/\omega$ [11, 12]. Taking into account (2), the stochastic resonance condition is written as follows [12]:

$$\omega_r = \pi \nu_0 \exp\left(-\frac{V_0}{D}\right). \tag{6}$$

It should be noted that the phenomenon of stochastic resonance itself does not lead to a directional particle motion. However, collective nature of the synchronous displacement of a large number of particles with subsequent migration in the elastic stress fields present in semiconductor crystals can undoubtedly cause a significant macroscopic response.

3. Application

The obtained results can be useful, in particular, for substantiating the experimental data on the transformation of the surface morphology of semiconductor compounds (GaN, GaP, GaAs) after treatments with a pulsed magnetic field with an amplitude induction value equal to 60 mT, presented in [9, 14].

In these works, the change in time of such parameters as the average values of roughness and the maximum height of nanoroughness of the surfaces of semiconductor compounds GaN, GaP and GaAs after the magnetic-field treatments was investigated. In general, this change did not exceed several lattice parameters and was reversible [9, 14].

Such changes in surface morphology can be explained by assuming that they are caused by redistribution of point defects – impurity atoms and ions. This assumption is consistent with [15–18], where, when studying the effect of a weak magnetic field on the micromechanical and electrophysical characteristics of silicon, an increase in the diffusion and adsorption activity of such point defects as positively charged ions of potassium, sodium, calcium, aluminum and negatively charged hydroxyl groups OH^- in the near-surface layers and on the surface was observed.

In turn, stochastic resonance may be the cause of particle evolution in III-V crystals. Let us estimate the frequencies of stochastic resonance. In particular, calculation by formula (6) at $V = 0.2$ eV yields the value of the frequency of stochastic resonance of defects $\nu_r = \omega_r/2\pi = 1.3$ GHz. Therefore, a necessary condition for stochastic resonance is the effect of an electromagnetic field of a given frequency on a semiconductor structure.

As shown in [9, 14], in a pulsed magnetic field with an amplitude induction $B = 60$ mT, free electrons in *n*-GaAs, *n*-GaN and *n*-GaP generate electromagnetic waves at cyclotron frequencies ν_B of 27, 8.4 and 2.1 GHz, respectively. The spectral lines of the cyclotron radiation of electrons in a semiconductor crystal are not infinitely narrow, since charge carriers experience scattering by phonons and defects when moving under the action of a magnetic field.

This leads to a broadening of the cyclotron radiation line in both directions relative to the given frequency values. On the other hand, the induction of a pulsed magnetic field at the moments of its increase and decrease is orders of magnitude smaller than the amplitude value. Accordingly, the cyclotron frequency will be significantly lower than the values given above. Consequently, electromagnetic oscillations in a wide frequency range, including those at 1.3 GHz, will be generated in a semiconductor crystal.

It should be noted that a similar situation occurs when microwave radiation acts on semiconductor crystals. Indeed, in resonators with a low quality factor, electromagnetic oscillations of a wide frequency range relative to the magnetron carrier frequency of 2.45 GHz are excited [8].

Therefore, stochastic resonance may be another possible mechanism of transformations of point defects in the near-surface region and on the surface of semiconductors under the action of microwave radiation and pulsed magnetic fields. Other possible mechanisms include vibration of molecules and variation of the dielectric constant of the substance [19, 20], nonthermal phonon distributions of microwaves [5], ponderomotive action of microwaves [21], decrease of the activation energy [22, 23] as well as resonance-related mechanisms [7–9].

4. Conclusion

Stochastic resonance is a possible mechanism of transformation of ensembles of point defects in III-V semiconductor compounds with covalent polar bonds under the action of microwave radiation and pulsed magnetic fields. Statistical synchronization occurs when the average waiting time of the transition between two potential wells stimulated by thermal fluctuations is equal to half the oscillation period of the periodic external electric force.

In particular, stochastic resonance can cause a transformation of the surface morphology due to the enhancement of the migration activity of point defects in the near-surface region and on the surface of III-V semiconductor compounds under the influence of microwave radiation and pulsed magnetic fields. The results of calculations of the stochastic resonance frequency, which confirm this idea, are presented. Since a certain proportion of ionic bonding is also inherent in III-V crystals, the proposed mechanism can be used to interpret the results of non-thermal exposure to microwave radiation [24–26].

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Milenin G.V.: conceptualization, writing – original draft, validation, methodology, writing – review & editing.

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Стохастичний резонанс як механізм трансформації дефектів у напівпровідникових сполуках при дії електромагнітних та магнітних полів

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Анотація. Обговорюється явище стохастичного резонансу дефектів напівпровідникових сполуках $A^{III}B^{V}$ при дії мікрохвильового випромінювання та імпульсних магнітних полів. Вивчено особливості резонансної трансформації ансамблів частинок, що підкоряються статистичним закономірностям. Результати застосовані для обґрунтування змін морфології поверхні напівпровідникових сполук A^3B^5 після обробки імпульсним магнітним полем. Наведено оцінку частоти стохастичного резонансу.

Ключові слова: напівпровідник, дефект, надвисокочастотне випромінювання, магнітне поле, стохастичний резонанс.