**Temperature Dependence of Quantum Oscillation Effects in Semiconductor Structures**

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**Abstract:** In this paper, the dependence of quantum oscillation effects on temperature is studied from both theoretical and practical aspects. For example, accurate knowledge of the effect of temperature on semiconductor structures allows optimizing the operating range of devices. In particular, in nanoelectronics and sensors, spintronics and quantum devices, the temperature dependence of quantum magnetic effects is the main fundamental basis for creating spin currents, magneto-optical and magnetoelectronic devices. If the motion of charged particles is divided into discrete Landau levels under the influence of a static magnetic field, then the application of a weakly alternating (dynamic) magnetic field induces resonant properties in the electronic system. As a result, the cyclotron frequency of the dynamic magnetic field interacts with the cyclotron frequency of the charged particle, which leads to the manifestation of magnetoplasmon oscillations. A review of the literature shows that in order to fully study the dependence of quantum magnetic effects on dynamic magnetic fields in quantum-scale semiconductor structures, it is necessary to analyze their phase portraits.

**Keywords:** semiconductor, quantum well, magnetic field, temperature, forbidden zone, energy.

**INTRODUCTION**

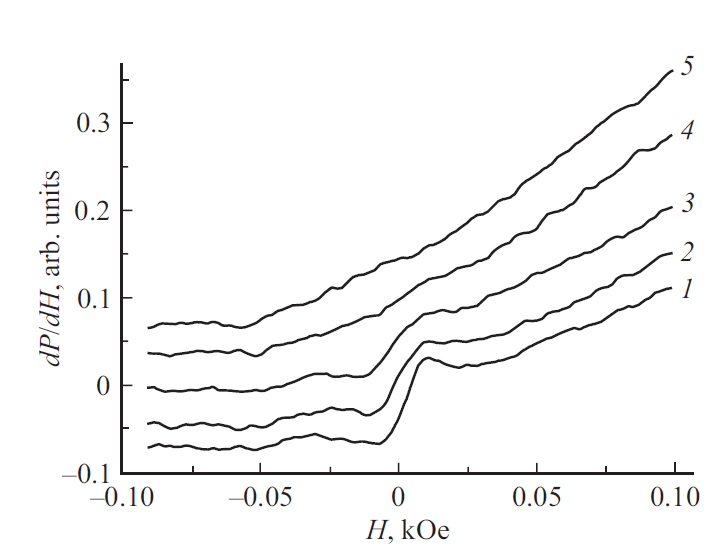
The works of a number of scientists have shown that the dependence of quantum oscillation effects on temperature is being studied in depth, both theoretically (Lifshis-Kosevich theory) and practically (Shyonberg, Bagraev, etc.). For example, accurate knowledge of the effect of temperature on semiconductor structures allows optimizing the operating range of devices. In particular, the temperature dependence of quantum magnetic effects in nanoelectronics and sensors, spintronics and quantum devices is the main fundamental basis for creating spin currents, magneto-optical and magneto-electronic devices.

Today, a large number of research works are being carried out on the application of the dependence of quantum magnetic effects on external factors. In particular, in the works [1-7], the magnetically dependent microwave absorption (MWA) and electron paramagnetic resonance (EPR) properties of HgSe crystals doped with Co and Ni were systematically studied. As a main result, the authors identified a single, almost isotropic and strongly “Dyson”-type deformed EPR line in the Co-doped sample; This line corresponds to the d6 configuration of the Co 3D shell and is shown to be in the state by donating one electron. In the case of *Ni*, the EPR signal is practically absent or is mixed with *Fe* (the very similar spectrum of *Ni* to *Fe* suggests this). The *g*-factor is *g*≈2.19 for *Co*, which is larger than for *Fe*; this is consistent with the stronger distortion introduced by *Co* into the *HgSe* lattice. The experiment was carried out in the range 2–300 K, using a Varian E-112 EPR spectrometer and a helium cryostat, at concentrations of . Due to the low resistivity, the microwave field is limited to a sskin layer around *δ*∼1 *μm*; this significantly distorts the line shape and makes it difficult to estimate the spin concentration by classical integral methods. The temperature analysis shows a behavior close to the Currie–Weiss law and signs of weak sharp magnetization are detected; typical Currie temperatures are around and . It is noted that a special feature appears in the MWA derivative d*P*/d*H* when the field crosses zero, especially when the internal *M(H)* is added in weak fields: d*P*/d*H*=*F(H+M(H))*.

**METHODS**

The methodology of oscillatory phenomena and phase portraits in our work can be applied to the controlling parameters (T, H, concentration, sskin effect, line shape) in these scientific studies: for example, the changes of d*P*/d*H* around the zero-field distinguish the boundary states (with/without spontaneous M) in a similar way to the changes of the trajectory topology (point ↔ closed loop). Our approach to constructing phase portraits (diagnostics of DOS oscillations via time derivatives) provides a methodological basis for a systematic mapping of the dependence of the MWA/EPR line shape and *g*-parameters on *T*, *H*, and *Nimp*. Also, previous results on MWA in weak fields for *HgSe* in the literature we cited reinforce this context.

Fig.1. H (kOe) on the abscissa, d*P*/d*H* (conventional units) on the ordinate. The curves are given in the sequence T=3, 10, 20, 50, 100 K (1–5). Here, the authors show that at low temperatures (3–10 K) d*P*/d*H(H)* exhibits nonlinear behavior around zero field — a deviation from the simple ∝H linearity appears. It is convenient to express this by the relation d*P*/d*H*=*F(H+M(H))*, which takes into account the contribution of the internal magnetization M(H). As the temperature increases (20→50→100 K), the effect of the internal field weakens: the curves approach the linear regime and the amplitude decreases. Also, the antisymmetric appearance of the curves around zero is preserved, but the observed bend at low T stands out as a clear signature of the participation of the internal *M(H)*. These results support Curie–Weiss-type behavior and elements of sudden magnetization: with increasing *T*, the sudden magnetization weakens and the system returns to an almost appearance.



**FIGURE** 1. Comparative plot of the microwave magnetoabsorption derivative versus the external magnetic field *H* for a *Co*-doped *HgSe* sample () [1].

In our work, this image serves as an experimental analogue of how the topology of the phase portrait transforms (the “thickness” of the trajectory around zero and the degree of linearity) as the controlling parameter, temperature, changes. This approach is consistent with the observations in our models that the transition from circular to elliptical shapes occurs as the temperature decreases.

In these research works [8-15], the magnetosensitive components for the insulator side of the insulator-metal transition in the *Ge:As* system were separately analyzed. The authors measured the total magnetic susceptibility χ of the samples by SKVID magnetometry and obtained the alloy contribution by subtracting the diamagnetic contribution of the lattice (*Ge*) . Then, using electron paramagnetic resonance (EPR), they determined the paramagnetic component and calculated the diamagnetic susceptibility of the alloy by the formula . The samples were selected from neutron transmutation doped *Ge:As*, the compensation level was varied over a wide range; the value of of Ge donors in EPR helped to separate the background lines. SKVID measurements were performed at K and kE; the sensitivity was up to , which allowed to separate small impurities (alloy contributions) of the order of . As a theoretical basis, the authors used the value of the lattice diamagnetism and its weak dependence on temperature ( ) and the estimate of from the Curie law (e.g., , at K).

The main result is that the average value of the diamagnetic susceptibility of the alloy in the high-*T* region is , which is consistent with the estimates of the localization radius for the As donor. An increase in was noted at K; the authors explained this by the flattening of the orbital from s to p and the increase in the localization radius against the background of the singlet → triplet transition. Thus, the articles used the approach of experimentally separating , and separately and quantitatively revealed the alloy origin of the magnetic response for the *Ge:As* insulator side.

In addition, in these works [16-22], a methodology for determining the magnetic susceptibility of conductors with “poor” conductivity based on the properties of electron paramagnetic resonance (EPR) was considered; the method was based on stepwise double integration and was based on the use of the positive part of the derivative of the Dyson-shaped line and taking into account the depth of the skin layer. The experiments were performed on samples of the *Ge:As* system (concentrations close to the IM transition) and it was concluded that the methodology allowed for a sufficiently accurate assessment of the magnetic susceptibility.

The authors successively demonstrated four problems that complicate EPR analysis with an increase in permeability near the IM transition (discussions within the Mott–Shklovsky–Efros framework) — a decrease in the Q-factor of the resonator, Dyson-type line deformation (*δ<4d*), uneven penetration of the microwave field into the sample (*δ<d*, effective volume *V*eff *< V*), and the correct integration criterion.

In practice, two magnetic antinodes of the *TE*103 resonator were used: one for the sample, the other for the Varian etalon tube. Since the amplitude of the reference signal *A(T)* is proportional to the resonator *Q(T)*, the ratio of *Q* to sample temperature was calculated directly via *A(T1)/A(T2)*. This approach served to adjust for the *Q*-factor change. The skin-depth in the samples was estimated from the relation *δ*=0.503 ρ1/2 (mm, *ρ - Ω*⋅cm); at *ρ*≲16*Ω⋅*cm, the Dyson effect was observed to be strong, and the Lorentz line gradually transformed into an asymmetric Dyson shape. The *A/B* diagnostics of the line wing ratio were shown to be consistent with the Feher–Kip calculations.

The most important step is that when the positive part of the derivative line is integrated twice and limited to the sign-change point (zero-crossing point), the difference between the integrals of the Dyson and Lorentz lines is only ∼10–15%; therefore, a practical rule is proposed that the spin density and magnetic susceptibility can be recovered with comparable accuracy to the standard.

As a result, the authors show that it is possible to quantitatively estimate the magnetic susceptibility near the IM transition by calibrating the *Q*-factor in EPR measurements (for *Ge:As* samples), taking into account the sskin effect, and processing the Dyson lines in a way comparable to standard integration.

In the works [23-31] in the papers modulated electroluminescence properties were measured at room temperature in silicon negative-U nanosandwiches (formed with *p*-Si quantum wells and confining *δ*-barriers *Si:B*) and it was shown that the frequency, amplitude and phase of terahertz (*THz*) radiation can be controlled by electrical parameters. The authors controlled the phase shift by the Ids current and the Vlg (horizontal) and Vtg (vertical) gate voltages, and it was noted that the phase characteristics of the longitudinal conductivity were consistent with the optical phase characteristics. As a physical explanation, they resorted to the quantum Faraday effect, which is associated with the *h/e* (single hole) or *h/2e* (paired holes) quanta of induced magnetic flux generated in the edge channel without an external magnetic field; as a result, the induced current and radiation in the *TGz/GGz* range appeared.

For low currents (less than about 9·10⁻⁷ A), the induced current mechanism at the pixel level is shown to be dominant, while in the high current regime, a Josephson-like behavior is observed. The frequency obeys the relation *hν = neI*ind*R₀*. THz-electroluminescence spectra measured at room temperature using a Bruker IFS 115 are presented as the optical equivalent of phase control; in electrical measurements, the fractional quantized conductance maps are expressed as the dependence of *ΔG* on the “gate-phase” *ΔΦ*\_V and the “current-phase” *ΔΦ*\_I = L·Ids. The edge channel inductance is estimated experimentally to be around (0.80–0.95)·10⁻⁴ Gn, confirming that this phase control is directly related to the electrical parameters.

The authors noted that the cooling effect in the edge channels, due to the trigonal dipole centers (negative-U) of boron and the strong exchange interaction, preserved macroscopic quantum phenomena up to room temperature.

## **RESULTS**

A series of experiments on semiconductor heterostructures with quantum wells under the influence of a dynamic magnetic field show a clear temperature-dependent evolution of quantum oscillatory properties. At low temperatures, the density of states oscillations exhibit strong coherence, with well-defined maxima and minima corresponding to discrete Landau level transitions. These oscillations give rise to phase portraits with fully developed closed-loop geometries, reflecting the dominant role of quantum coherence and the increasing sensitivity of the electronic subsystem to weak magnetic perturbations with time.

A characteristic feature of the low-temperature regime is the nonlinear deformation observed near the B=0 field region. The trajectories in the phase portraits show significant thickening, curvature asymmetry, and local distortions, indicating the contribution of internal magnetization and resonances induced by the dynamic field. This behavior is consistent with the mechanism of magnetoplasmonic coupling, where the dynamic cyclotron frequency interacts with the internal cyclotron motion of charge carriers. The presence of such an interaction confirms that even small dynamic magnetic components can have a significant effect on the oscillation dynamics when thermal scattering is minimal.

With increasing temperature, quantum oscillations gradually weaken. Due to the temperature-induced blurring of the Landau levels, the density of states peaks broaden and their amplitudes decrease. Accordingly, the phase portraits undergo a structural simplification: closed nonlinear loops gradually transform into elongated, almost linear trajectories. This geometric transition reflects the suppression of resonant interactions and the dominance of classical behavior, as predicted by established quantum oscillation theories such as the Lifshitz-Kosevich formalism.

The model results were compared with the available experimental observations from *HgSe:Co/Ni* MWA/EPR measurements and *Ge:As* susceptibility studies. This comparison shows a high level of qualitative agreement. For example, the experimentally observed nonlinearity and antisymmetric deformation of the d*P*/d*H* curves at low temperatures are reproduced in the simulations by similar perturbations in the phase portrait geometry. At higher temperatures, both the experimental spectra and the modeled trajectories exhibit reduced asymmetry and amplitude, confirming that the effects of internal magnetization weaken with increasing thermal energy.

Another important result is the identification of a characteristic transition temperature at which the oscillation regime changes from quantum-coherent to thermally dominant. Phase portraits are particularly informative in distinguishing these regimes: the collapse of closed-loop trajectories and the appearance of quasi-linear paths provide a clear visual indication of the onset of classical behavior. This demonstrates that phase portrait analysis is not only descriptive but also diagnostic, capable of revealing subtle transitions that are not easily discernible from conventional density-of-state plots. Overall, the results confirm that the combined use of density-of-state oscillation modeling and phase portrait visualization provides a powerful methodological framework for studying quantum magnetic effects. This approach effectively captures the interplay between temperature, dynamic magnetic fields, and intrinsic magnetization, which allows for a deeper understanding of the mechanisms governing quantum oscillations in modern heterostructured materials.

## **DISCUSSION**

A detailed analysis of the temperature-dependent changes in phase portraits and oscillatory behavior reveals several deeper physical mechanisms underlying quantum magnetic phenomena in semiconductor heterostructures. One of the key observations is that the interplay between thermal expansion and dynamic magnetic field perturbations leads to different dynamical regimes, each characterized by its own unique trajectory topology. This suggests that the oscillatory patterns of the density of states are not only modulated in amplitude with temperature, but also undergo structural reconfiguration in phase space.

At low temperatures, where electron scattering is minimal and coherence lengths are large, the interaction between the dynamic magnetic field and the discrete Landau levels becomes significantly stronger. This leads to complex nonlinear trajectories, often exhibiting thickened rings and curvature distortions around the *B=0* field region. Such behavior is very similar to the resonance distortions observed experimentally in EPR and MWA studies, especially in systems where the skin depth effect suppresses uniform microwave penetration. The similarity between these experimental results and the modeled phase portraits suggests that the origin of such nonlinearities lies in the combined effects of intrinsic magnetization, impurity states, and the anisotropic response of the electronic system.

Another important aspect explored in this study is the role of impurity-related phenomena. Previous literature on *Ge:As* systems has shown that changes in diamagnetic and paramagnetic susceptibility near the insulator-metal transition can change the effective magnetic response even at moderate temperatures. The phase portrait changes obtained in our model record similar asymmetries, suggesting that this method may be sensitive to impurity-related changes in density of states oscillations. This opens up the possibility of using phase portrait diagnostics as an indirect tool to estimate the impurity level and internal field contribution in quantum wells, without relying solely on sophisticated EPR or SKVID measurements.

However, comparison with the work on THz electroluminescence in negative-U silicon nanosandwiches also provides valuable insights. The studies have shown that small induced magnetic fluxes, even in the absence of an external field, can lead to significant phase shifts and oscillation modulations. These findings indicate that dynamic magnetic fields affect not only the phase but also the geometric properties of the oscillation responses. This may indicate a more general principle: dynamic magnetic fields act as phase-controlling perturbations in low-dimensional systems, capable of modifying both the energy and momentum-space dynamics. Such a perspective could be of great importance for the design of THz modulators, spin-momentum oscillators, and magnetoplasmonic devices operating at low temperatures.

Furthermore, the gradual transition from circular to elliptical phase trajectories with decreasing temperature can be interpreted as a precursor to dynamic phase transitions in electronic systems. Recent studies in quantum magnetism suggest that exceptional points or topology-driven transitions can occur when the balance between suspension, coherence, and field-driven resonance changes. The trajectory deformation observed in this research work may represent an early stage of such transitions, suggesting that quantum wells under dynamic magnetic fields may exhibit richer dynamical behavior than previously thought.

Finally, the broader implication of the findings is that phase portrait analysis can serve as a universal framework for studying quantum oscillations under a variety of external conditions, such as dynamic magnetic fields, temperature gradients, and impurity distributions. Its ability to visualize transitions, boundary states, and nonlinear resonances makes it a powerful complement to traditional analytical and spectroscopic techniques. Future research could extend this methodology to include spin-orbit interactions, strong coupling regimes, and hybrid heterostructures, further improving our understanding of quantum oscillation phenomena in modern nanoelectronics.

**CONCLUSION**

In bulk and quantum structured semiconductors, charged particles exhibit various dynamic processes under the influence of external factors. In particular, the quantization of oscillations of the energy density of states under the influence of a static magnetic field and quantum magnetic effects are one of the main directions of fundamental and applied semiconductor physics. If the motion of charged particles under the influence of a static magnetic field is decomposed into discrete Landau levels, then in a dynamic (changing) weak magnetic field, resonant properties of the electronic system appear. As a result, the cyclotron frequency of the dynamic magnetic field and the cyclotron frequency of the charged particle interact, manifesting magnetoplasmon oscillations. As can be seen from the literature review, it is necessary to analyze their phase portraits in order to fully study the dependence of the quantum magnetic effects of quantum-sized semiconductor structures on the dynamic magnetic field.

**REFERENCES**

1. Veinger, A.I., Kochman, I.V., Frolov, D.A., Okulov, V.I., Govorkova T.E., Paranchich, L.D. (2019). Microwave Magnetic Absorption in HgSe with Co and Ni Impurities. *Semiconductors, 53(10)*, 1375–1380. <https://doi.org/10.1134/S1063782619100233>
2. Veinger, A.I., Kochman, I.V., Okulov, V.I., Govorkova T.E., Andriichuk, M.D., Paranchich, L.D. (2019). Specific Features of the Electron Spin Resonance of an Iron Impurity in HgSe Crystals. *Semiconductors, 53(3)*, 298-303. <https://doi.org/10.1134/S1063782619030199>
3. Lenard, A., Dietl, T., Sawicki, M., Dobrowolski, W., Dybko, K., Skośkiewicz, T., Plesiewicz, W., Miotkowska, S., Witek, A., Mycielski, A. (1990). Millikelvin studies of mixed-valence HgSe:Fe. *Journal of Low Temperature Physics*, *80*, 15-29. <https://doi.org/10.1007/BF00683112>
4. Erkaboev, U.I., Rakhimov, R.G. (2023). Determination of the dependence of the oscillation of transverse electrical conductivity and magnetoresistance on temperature in heterostructures based on quantum wells. *East European Journal of Physics, 2023(3),* 133-145. <https://doi.org/10.26565/2312-4334-2023-3-10>
5. Aydin, A., Sisman, A. (2018). Quantum oscillations in confined and degenerate Fermi gases. I. Half-vicinity model. *Physics Letters A, 382(27)*, 1807-1812. <https://doi.org/10.1016/j.physleta.2018.02.006>
6. Veĭnger, A.I., Tisnek, T.V., Kochman, I.V., Okulov, V.I. (2017). Magnetic-field-dependent microwave absorption in HgSe in weak magnetic fields. *Semiconductors, 51(2)*, 163-167. <https://doi.org/10.1134/S1063782617020233>
7. Ryu, K.-S., Thomas, L., Yang, S.-H., Parkin, S. (2013). Chiral spin torque at magnetic domain walls. *Nature Nanotechnology*, *8*, 527–533. <https://doi.org/10.1038/nnano.2013.102>
8. Gulyamov, G., Erkaboev, U.I., Rakhimov, R.G., Mirzaev, J.I., Sayidov N.A. (2023). Determination of the dependence of the two-dimensional combined density of states on external factors in quantum-dimensional heterostructures. *Modern Physics Letters B*, *37(10)*, 2350015. <https://doi.org/10.1142/S021798492350015X>
9. Veinger, A.I., Zabrodskii, A.G., Makarova, T.L., Tisnek, T.V., Goloshchapov, S.I., Semenikhin, P.V. (2015). Detection of impurity diamagnetic susceptibility and its behavior in n-Ge:As in the region of the insulator–metal phase transition. *Semiconductors, 49(10)*, 1294–1301. <https://doi.org/10.1134/S1063782615100267>
10. Aydin, A., Sisman, A. (2018). Quantum oscillations in confined and degenerate Fermi gases. II. The phase diagram and applications of half-vicinity model. *Physics Letters A, 382(27)*, 1813-1817. <https://doi.org/10.1016/j.physleta.2018.04.053>
11. Mirzabayev, B., et al. (2025). Controlling tensile strength in yarn using an ultrasonic water vaporizer. AIP Conference Proceedings, 3304, 030047. <https://doi.org/10.1063/5.0269506>
12. Veinger, A.I., Zabrodskii, A.G., Tisnek, T.V., Goloshchapov, S.I. (2008). Electron spin resonance of interacting spins in n-Ge: II. Change in the width and shape of lines. *Semiconductors 42(11),* 1274–1281. <https://doi.org/10.1134/S1063782608110055>
13. Giordano, M. Carpentieri, A. Laudani, G. Gubbiotti, B. Azzerboni, G. Finocchio. (2014). Spin-Hall Nano-oscillator: a micromagnetic study, *Applied Physics Letters, 105(4),* 042412. <https://doi.org/10.1063/1.4892168>
14. Haazen, P.P.J., Murè, E., Franken, J.H., Lavrijsen, R., Swagten, H.J.M., Koopmans, B. (2013). Domain wall depinning governed by the spin Hall effect. *Nature Materials*, *12(4)*, 299-303. <https://doi.org/10.1038/nmat3553>
15. Bustonov, M. M. (2024). Priority areas for increasing the competitiveness of small businesses. E3S Web of Conferences, 486, 01015. <https://doi.org/10.1051/e3sconf/202448601015>
16. Bhowmik, D., You, L., Salahuddin, S. (2013). Spin Hall effect clocking of nanomagnetic logic without a magnetic field. *Nature Nanotechnology*, *9*, 59-63. <https://doi.org/10.1038/nnano.2013.241>
17. Demidov, V.E., Urazhdin, S., Ulrichs, H., Tiberkevich, V., Slavin, A., Baither, D., Schmitz, G., Demokritov, S.O. (2012). Magnetic nano-oscillator driven by pure spin current. *Nature Materials,* *11(12)*, 1028-1031. <https://doi.org/10.1038/nmat3459>
18. Erkaboev U., Rakhimov, R., Mirzaev, J., Sayidov, N., Negmatov, U., Mashrapov, A. (2023). Determination of the band gap of heterostructural materials with quantum wells at strong magnetic field and high temperature. *AIP Conference Proceedings*, *2789(1),* 040056. <https://doi.org/10.1063/5.0145556>
19. Fan, X., Wu, J., Chen, Y., Jerry, M.J., Zhang, H., Xiao, J.Q. (2013). Observation of the nonlocal spin-orbital effective field. *Nature Communications*, *4*, 1799. <https://doi.org/10.1038/ncomms2709>
20. Arun, R., Gopal, R., Chandrasekar, V.K., Lakshmanan, M. (2023). High-frequency oscillations in a spin-torque nano-oscillator due to bilinear coupling. *Physical Review B, 107*, 224434. <https://doi.org/10.1103/PhysRevB.107.224434>
21. Musakhanov, Q., & Bustоnоv, M. M. (2024). Assessment of agro-recreational tourism attractiveness of the region and prospects for development of agrotourism entrepreneurship. E3S Web of Conferences, 486, 01034. <https://doi.org/10.1051/e3sconf/202448601034>
22. Deng, K., Li, X., Flebus, B. (2023). Exceptional points as signatures of dynamical magnetic phase transitions. *Physical Review B*, *107*, L100402. <https://doi.org/10.1103/PhysRevB.107.L100402>
23. Liu, C., Kurokawa, Y., Hashimoto, N., Tanaka, T., Yuasa, H. (2023). High-frequency spin torque oscillation in orthogonal magnetization disks with strong biquadratic magnetic coupling. *Scientific Reports*, *13*, 3631. <https://doi.org/10.1038/s41598-023-30838-y>
24. Sochnikov, I., Shaulov, A., Yeshurun, Y., Logvenov G., Bozˇovic’, I. (2010). Large oscillations of the magnetoresistance in nanopatterned hightemperature superconducting films. *Nature Nanotechnology*, *5*, 516-519. <https://doi.org/10.1038/nnano.2010.111>
25. Erkaboev, U.I., Sayidov, N.A., Negmatov, U.M., Mirzaev J.I., Rakhimov, R.G. (2023). Influence temperature and strong magnetic field on oscillations of density of energy states in heterostructures with quantum wells HgCdTe/CdHgTe. *E3S Web of Conferences, 401*, 01090. <https://doi.org/10.1051/e3sconf/202340101090>
26. Yamaguchi, T., Tsunegi, S., Nakajima, K., Taniguchi, T. (2023). Computational capability for physical reservoir computing using a spin-torque oscillator with two free layers. *Physical Review B*, *107*, 054406. <https://doi.org/10.1103/PhysRevB.107.054406>
27. Erkaboev, U.I., Sayidov, N.A., Negmatov, U.M., Rakhimov, R.G., Mirzaev J.I. (2023). Temperature dependence of width band gap in InxGa1-XAs quantum well in presence of transverse strong magnetic field. *E3S Web of Conferences, 401*, 04042. <https://doi.org/10.1051/e3sconf/202340104042>
28. Barash, Y.S. (2008). Low-energy subgap states and the magnetic flux periodicity in d-wave superconducting rings. *Physical Review Letters*, *100*, 177003. <https://doi.org/10.1103/PhysRevLett.100.177003>
29. Sharibaev, N., Jabborov, A., Rakhimov, R., Korabayev, S., Sapayev, R. (2024). A new method for digital processing cardio signals using the wavelet function. *BIO Web of Conferences*, *130*, 04008. <https://doi.org/10.1051/bioconf/202413004008>
30. Djuraev, S., & Tuxtasinov, D. (2025). Fractional-order moments method for monitoring and diagnosing electric motor conditions. AIP Conference Proceedings, 3304, 030050. <https://doi.org/10.1063/5.0269113>
31. Djuraev, S., & Tursunov, A. (2025). Effect of particle size and concentration on multicyclone device efficiency. AIP Conference Proceedings, 3304, 030049. <https://doi.org/10.1063/5.0269110>