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Pseudomagnetic Field and Quantum Computing at Landau Levels in Nanographite Films

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ABSTRACT

Visualization of the pseudomagnetic field in nanographite films using optical radiation from Landau levels significantly simplifies magnetic field detection compared to the proposal by the authors of who used a scanning tunneling microscope at a temperature of 7.5 K to visualize Landau levels [1-2]. In our case, optical radiation measurements from Landau levels were conducted using a photodiode at room temperature. The existence of a stable Landau level staircase in nanographite films opens the possibility of quantum computing on Landau level qubits.

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It has been theoretically predicted that with a strong local distortion of the graphene lattice, electrons in the deformed area begin to travel along closed paths, as though they were in an external magnetic field [1]. Such a “field” is termed pseudomagnetic. The more the lattice deformation, the greater its magnitude. An investigation carried out by physicists from the USA and Spain verified the assumptions of theorists who demonstrated that electrons in deformed graphene can behave as if they were situated in a potent magnetic field. The outcomes of the experiment were reported in [2].

From the classical perspective, an electron in a magnetic field moves along a circular orbit, and its energy can assume any value; upon transitioning to a quantum-mechanical examination, the energy becomes quantized. Discrete energy magnitudes corresponding to movement in a plane perpendicular to the field are termed Landau levels. At the microscopic level of description, stretching a graphene sheet results in an anisotropic alteration in the hopping integrals between adjacent atoms. This alteration in the linear estimation can be construed as the appearance of a pseudo-magnetic field acting upon the electrons. It thought to be mentioned that the emerging magnetic field is not genuine, but in its chief aspects functions as a true magnetic field, yet unlike a real field, the pseudo-magnetic field does not breach time symmetry. It has been demonstrated theoretically and experimentally that uniform tension of a graphene sheet in one direction, upsetting the symmetry of the crystal lattice, results in the opening of a gap in the electron spectrum. If graphene is stretched symmetrically in all directions, then the pseudo-magnetic field acting on the electrons is uniform and leads to the generation of Landau levels.

Switching of Conductivity in Nanographite Films

In the instance of a nanographite (NG) film, the Landau levels are perceived as coherent levels of optical emission during the application of electrical voltage to the contact pads affixed to the surface of the NG film and varying within the extent from zero to 100 volts with an increase in current to a crucial magnitude of about 0.5 - 1 A [3]. In this situation, a leap in electrical resistivity by 4-6 orders of magnitude happens and a pseudomagnetic field is formed, observed utilizing optical emission from the Landau levels. The current-voltage profile and electrical switching events in the NG film are illustrated in Figure 1. At the transition point, the current abruptly shifts toward the metastable “OFF “condition, where the specific electrical resistivity is elevated compared to the “ON” condition by four to six orders of magnitude. After the voltage is removed, the sample reverts to the “ON” state with low resistance, allowing the switch to function anew. The sudden surge of the pseudomagnetic field at the instant of resistance switching results in intense heating and even vaporization of the film area beneath one of the electrical leads, meaning a minor char spot that is visible under a microscope.

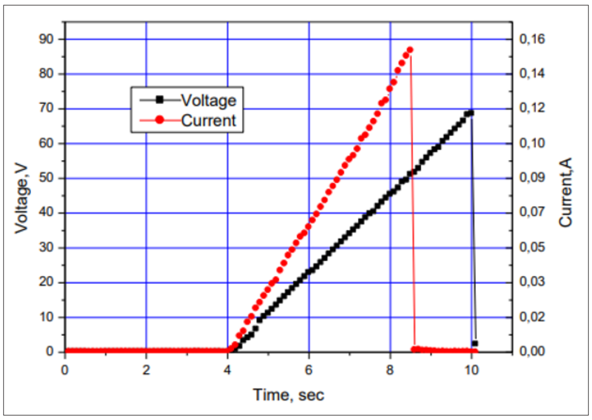

Figure 1: The current-voltage characteristic of a 1-µm-thick NG film on a quartz substrate at ambient temperature. As observed, the current stops before the voltage, implying the shutoff happens for an intrinsic reason, uniquely linked only to the current magnitude

Optical Radiation due to Switching of Conductivity

The transition state in the nanographite film is accompanied by a sharp heating, generating optical radiation and an effect resembling a pseudomagnetic field. This radiation is recorded using a photodiode [4]. The scheme for recording optical pulses is shown in Figure 2. The graph of the photodiode voltage dependence on the recording time is shown in Figure 3. As can be seen from the data, the energies of the recorded optical pulses correspond to discrete energy levels separated by a constant value of ΔE = 0.0022097 eV. The precise localization of the levels to the seventh decimal place indicates the coherence of the radiation and the similarity to Landau levels [5]. Optical and magnetic processes in nanographite films are caused by the dynamics of magnetic vortices in the Joseph medium of the film, which is described in detail in [4, 5]. The lower critical field value corresponding to the onset of penetration of magnetic vortices into the nanographite film, denoted as HC1, is approximately 0.22×10-8 T. The magnetic field penetration depth into the film reaches 0.95 mm [6]. As a result, the Earth's geomagnetic field easily penetrates the entire thickness of the nanographite film. Magnetic vortices moving within the film emit radiation upon reaching the NG film boundary, which is equal to 1 micrometer. Figure 3C shows that the interval between successive radiation pulses remains constant and equals 5×10-6 sec, which corresponds to a frequency of 2×105 Hz. The moments of light emission, when magnetic flux quanta emerge onto the NG film surface, are associated with the decay of Cooper pairs of current carriers.

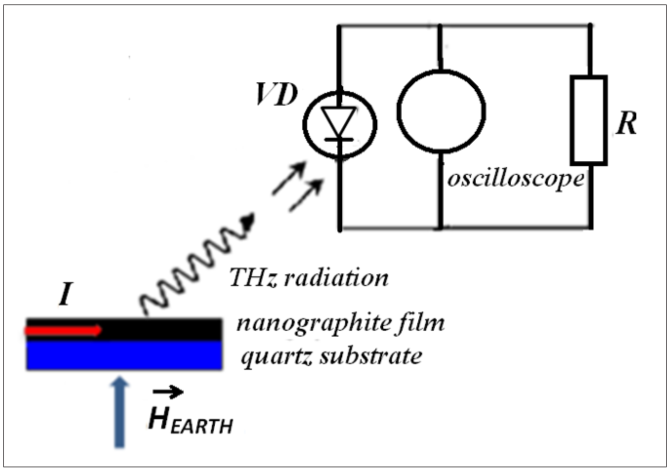

Figure 2: Optical Pulses Registration Scheme

Generation of Pseudo Magnetic Fields on the Landau Levels of NG Films

During the transition in the nanographite film, a significant increase in temperature is observed, which leads to the appearance of both optical radiation and thermomechanical stresses generating a pseudomagnetic field. The magnitude of the magnetic field ΔB, corresponding to the minimum energy gap between the Landau levels ΔE = 0.0022097 eV, is determined by the well-known formula:

$$\Delta B = \frac{\Delta E m_e^*}{e\hbar} = 0.66\ \text{T}, \quad (1)$$

Where $m_e^* = 0.03 m_e$ is the electron effective mass, e is the electron charge, $\hbar$ is the reduced Planck's constant.

According to the data presented in Figure 3A, the maximum voltage level achieved by the Landau levels is ΔE_{max} = 0.3 volts, which is equivalent to a total pseudomagnetic field of $\Delta B_{max} = \Delta E_{max}/\Delta E \times \Delta B$ = 90 Tesla. However, judging by Figure 3A, the photodiode has reached saturation, meaning the maximum voltage level and pseudomagnetic field may be significantly higher. A linear approximation of the peak in Figure 3A allows us to estimate the maximum pseudomagnetic field to be 380 Tesla. The laboratory record for the induction of constant magnetic field that lasted for thousandths of a second is only 85 T [2].

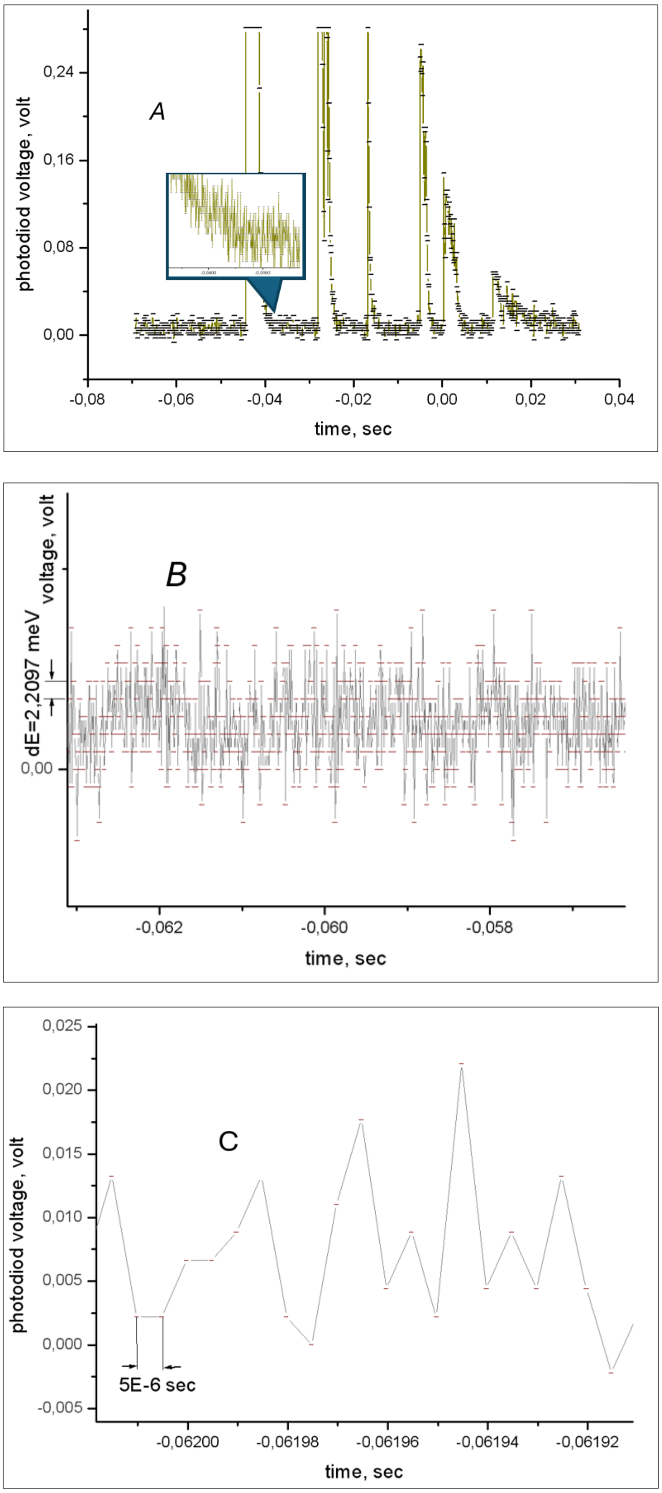

Figure 3: Photodiode voltage versus recording time: A — general view of the functional relationship; the insert- structure

of Landau levels on the avalanche section of photodiode signal, B — enlarged fragment of graph A, allowing one to discern the linear structure of the energy spectrum (Landau levels); B — graph with maximum magnification, demonstrating the temporal structure of the photodiode signal. It can be seen that the minimum distance between the emission points of optical pulses is 5 μs. Regular repetition of pulses with an interval of 5 μs indicates the movement of magnetic quanta through the thickness of the NG film at a speed of 0.2 m/s.

Quantum Computing at Landau Levels in Nanographite Films

The existence of a stable Landau level staircase in nanographite films (see Fig.3) opens the possibility of quantum computing on Landau level qubits. Moreover, as can be seen in the inset in Fig.3, there are a large number of Landau levels, which allows for the organization of quantum computing based on qudits. As can be seen in Fig.3, for a total voltage jump on the photodiode of 0.3 *V* or more, the number of Landau levels formed will be 0.3/0.0022097 ≥ 136. Temperature conditions: to avoid spontaneous transitions, it is necessary: $k_B T \ll E_j$, where is the Josephson energy, which can be defined by the relation:

$E_j = \frac{I_c \Phi_0}{2\pi}$, where I_c is the critical current for nanographite film equal to 0.8 μA, Φ0 is the magnetic quantum [6]. Therefore, for the standard qubit with the frequency f_J =4.3 GHz one obtains the value Ej= 6,58×10^{-24} J which corresponds to heating up to T_{max} ~ 0.2 K. That is the cryogenic cooling up to 20 mK is required. For the NG film f_J =424 GHz, which is 42 times higher than f_J for standard Josephson qubits.

To convert a qubit from |0⟩ to |1⟩, a pulse with a frequency of f_J =424 GHz is required, which allows for a two-order-of-magnitude increase in information processing speed compared to a standard qubit.

Discussion

Despite the difference between graphene and graphite the authors of observed the QHE in graphite crystals that are up to hundreds of atomic layers thick [7]. Visualization of the pseudomagnetic field in nanographite films using optical radiation from Landau levels significantly simplifies magnetic field detection compared to the proposal by the authors of who employed a scanning tunneling microscope at a temperature of 7.5K to visualize Landau levels [2]. In our case, optical radiation measurements from Landau levels were conducted using a photodiode at room temperature. Simple estimates of thermal stress in nanographite films allow us to assess the mechanism of pseudomagnetic field formation. In essence, this assessment boils down to the well-known

relationship: $\frac{l_B}{l} = \alpha \Delta T$, where a is the thermal expansion coefficient of the NG film on the quartz substrate, *l* is the size of the hot spot on the NG film surface at the moment of the maximum magnetic field jump, which can be determined using a microscope as the melting point on the film surface. The avalanche-like growth of the pseudomagnetic field at the moment of resistance switching leads to strong heating and even evaporation of the film region under one of the electrical contacts, i.e., a small burnout spot that can be observed under a microscope. A similar phenomenon of super injection and breakdown of the film surface was observed in the case of carbyne film [8]. The $l_B = \sqrt{\frac{\hbar C}{eB}}$ is the magnetic length, *ħ* is the reduced Planck's constant, *C* is the speed of light , *e* is the electron charge, B is the magnetic field induction, ΔT is the temperature difference during film heating at the peak magnetic field ΔT≈ E_{max}/k_B≅3500K, where E_{max}=0.3 eV, as shown in Fig. 3. Regarding the thermal expansion coefficient, a of the NG film, it is necessary to account for the expansion of both the film itself and the quartz substrate. The overall value a is ~ 5×10^{-6} K^{-1}. The corresponding calculations yield a magnetic induction of *B* = 200 Tesla with l ~ 100 nm. The sharp optical jumps in Fig. 3A correspond to magnetic pulses of the avalanche-like magnetic flux arising due to thermomagnetic instability [9]. To test the thermomagnetic instability hypothesis, we analyze Fig. 3 in more detail. Let us define the ratio of the magnetic diffusion coefficients D_m and thermal diffusion coefficients D_t:

$$\tau = \frac{D_m}{D_t} = \frac{\mu_0 \sigma K}{C}, \qquad (2)$$

where μ0 = 4**π**•10^{-7} Hm^{-1} is the magnetic constant, σ = 100 Ohm-1m-1 is the conductivity, K = 130 W $m^{-1}K^{-1}$ is the thermal conductivity and C = 7•10^5 J $m^{-3}K^{-1}$ is the heat capacity of the nanographite film. Then, τ ≅10^{-8}<<1.This corresponds to the case of a hard superconductor with viscous magnetic flux, when the time of magnetic flux change is much shorter than the time of temperature change. Importantly, in the adiabatic operating mode of the nanographite film, the heat generated by the abrupt change in magnetic flux is released instantaneously and locally and cannot diffuse due to cooling on the considered time scale.

The coherence time for a nanographite film can be estimated using Figure 1 as a few milliseconds, which significantly exceeds the 200 μs for a standard qubit using Josephson junctions.

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