2D electron gas density of states at the Fermi level in silicon nanosandwich

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Abstract. The two-dimensional density of states at the Fermi level for integer filling factors was calculated based on the results of observation of the de Haas–van Alphen effect on a silicon nanostructure at room temperature and according to the equilibrium thermodynamics relations.

1. Introduction
In the present work, we measured the magnetization of the silicon sandwich-structure with a step-by-step sweep of magnetic field. Using a discrete sweep with a step of 1 Oe, it was possible to resolve the oscillations in the de Haas–van Alphen effect with integer filling factors up to \( \nu = 12 \), inclusive.

The two-dimensional thermodynamic density of states (DOS) at the Fermi level was determined from the field dependence of the magnetization of the sample obtained by implementing a quasistatic process, which gives grounds to analyze the oscillations observed in the experiment in the framework of equilibrium thermodynamics. The purpose of this work was to analyze a contribution of edge channels to the density of states in the vicinity of the Fermi level in the framework of equilibrium thermodynamics.

2. Experiment
The investigated silicon sandwich-structure is the ultra-narrow, 2 nm, p-type quantum well (Si-QW) confined by the delta barriers heavily doped with boron on then-type Si (100) surface [1] (figure 1 (a)).

The confinement of the carriers’ motion by negative-U dipole boron centers made it possible to achieve extremely low effective mass of the carriers and suppress the electron-electron interaction, which determined the possibility of implementing the strong field criterion at room temperature [2, 3] (figure 1 (b, c)).

The two-dimensional carrier density required for further calculations was found from Hall measurements [1].
The magnetic properties of silicon nanostructures were studied by analyzing the field dependences of the magnetization of samples measured by the Faraday method at room temperature in the interval from 75 to 550 Oe with a discrete sweep of an external magnetic field with a “step” of 1 Oe on a setup created on the basis of an MGD 312 FG spectrometer, in automatic mode (figure 2). The setup was calibrated using a single crystal of magnetically pure indium phosphide with a susceptibility \( \chi = -313 \times 10^{-9} \text{ cm}^3/\text{g} \) as a reference sample. The sample mass was determined on a BP 211 D scale with an accuracy of \( 10^{-5} \text{ g} \). The sample was oriented relative to the external magnetic field, taking into account the comments made by prof. Schoenberg [4], which made it possible to avoid “smearing” of oscillations due to averaging of the magnetic field on the linear size of the structure in the direction of the magnetic field gradient.
3. DOS at the Fermi level

In equilibrium thermodynamics, the Helmholtz free energy is given by \( G = PV - TS - MH + \mu N \), where \( M \) is the magnetic moment of the sample, \( \mu \) is the chemical potential, \( N \) is the number of particles, and \( B \approx H \). Hence

\[
\frac{\partial M}{\partial \mu} = -\frac{\partial}{\partial \mu} \frac{\partial G}{\partial H} = \frac{\partial}{\partial H} \frac{\partial G}{\partial \mu} \Rightarrow \left( \frac{\partial M}{\partial \mu} \right)_H = - \left( \frac{\partial N}{\partial H} \right)_\mu
\]  

(1)

Using this Maxwell relation (1) and the linear dependence of the degree of degeneracy \( g \) on the strength of an external magnetic field, we get the relation

\[
\frac{\Delta M}{N} = \frac{\Delta \mu}{H^*},
\]

(2)

where \( \Delta M \) is the oscillation magnitude of the magnetic moment, \( H^* \) is critical field value, \( N = p_{2d} \cdot S \). Let \( \Delta \mu \approx \Delta W \) be the effective energy gap. Then

\[
\Delta W = \frac{H^* \Delta M}{N}.
\]

(3)

With a change in the magnetic field by \( \Delta H \), the number of states that have passed through the Fermi level is defined as \( v \Delta g \). Consequently, the residual number of states in the gap between Landau levels \( N_g = v \Delta H g / H^* = N \Delta H / H^* \). Further, by \( \Delta H \) we mean the change in the magnetic field strength between the local maximum and minimum of the oscillations of the magnetization at integer filling factors differing by one.

If \( D_g \) is the average two-dimensional density of states (DOS) at the Fermi level in the interval of magnetic fields \( \Delta H \), then

\[
N_g = D_g \cdot \Delta W.
\]

(4)

From (4) we express the two-dimensional density of states and transform as follows, taking into account (2) and (3):

\[
D_g = \frac{N_g}{\Delta W} = \frac{N \cdot \Delta H / H^*}{N / H^* \cdot \Delta M} = \frac{N^2 \Delta H / H^* \Delta M}{H^* \cdot \Delta M} = \frac{p_{2d}^2 S^2 \Delta H}{H^* \cdot \Delta M}.
\]

Expression (5) makes it possible to estimate the average DOS \( D_g \) at the Fermi level in the interval \( \Delta H \), i.e. DOS value between the upper occupied and lower uninhabited Landau levels.

4. Selection of the computational model and the calculation of the density of states

Studies conducted at low temperatures and in high magnetic fields showed that the density of states in a spatially confined two-dimensional electron system is characterized by peaks in the vicinity of Landau levels and small values in each of the energy gaps resulting from the bending of the levels up [5]. To describe the experimental results, various models of the density of states can be used, which differ primarily in the choice of the statistical distribution function.

For example, analyzing the results obtained from the measuring of the specific heat of GaAs – GaAlAs films, Gornik et al. [6] considered models with a Gaussian and Lorentz distribution functions and showed that the best approximation is to use a Gaussian density of states with a flat base background. Moreover, an increase in the sample temperature leads to a broadening of the Gaussian distribution and the appearance of a noticeable contribution of states between Landau levels to the total density of states. The results [6] correspond to theoretical predictions [7].
Wiegers et al. [8] successfully used to describe an experiment to measure the magnetization of AlGaAs-GaAs monolayer heterostructures, a simplified model proposed by Ando and Uemura [9].

On the other hand, it is obvious that the main difference in the correspondence of one or another DOS distribution function to experimental dependences is manifested only in high magnetic fields. While in low magnetic fields, which is our case, this difference is small.

Therefore, we estimate the density of states between the Landau levels (at the Fermi level), based on the simple model proposed [8], which takes DOS constant between neighboring Landau levels and takes into account the features in the experimental data.

Following [8], we assume that the “width” ΔH of oscillations of the magnetization at integer filling factors is proportional to the number of states in the gap. For example, for the oscillation observed in the field $H^* = 414\, Oe$ ($\nu = 3$), we have $\Delta H \approx 6\, Oe, \Delta M \approx 8,31 \times 10^{-10}\, er\, G$. Then we get

$$D_g = \frac{9 \times 10^{10} (0,94 - 10^{-2})^2}{(414)^2 \times 8,31 \times 10^{-10}} = 3,35 \times 10^{19}\, er\, G^{-1}. \quad (6)$$

The density of states at the Fermi level for a number of integer filling factors and its dependence on the filling factor are shown in figure 3.

![Figure 3](image.png)

**Figure 3.** The dependence of the density of states in silicon nanosandwich on the filling factor at room temperature.

5. Results

The study of the thermodynamically equilibrium parameters of the system has certain advantages compared to those measured through transport effects, where Fermi level pinning takes place in the regions of localized states that do not conduct current. When measuring the specific heat and magnetization, the difference between localized and delocalized states does not matter [10]. Therefore, the equilibrium characteristics show the total density of states, and using the oscillating dependences of the magnetization, one can investigate the thermodynamic density of states in a magnetic field, which is an integral characteristic of the energy spectrum of the structure.

Current-carrying edge states are introduced as intersections of the Landau levels and the Fermi level at the edges of the sample [11]. Thus, the total number of edge states is equal to the filling factor — the number of filled Landau levels.
In theoretical studies, no special attention was paid to the dependence of the DOS value between the Landau levels on the magnetic field and the filling factor. However, in [12], a strong decrease in DOS between Landau levels with a magnetic field was predicted, assuming spatial correlations of a random potential.

In an experimental study [5], performed on a 2DES formed in a modulated AlGaAs-GaAs heterojunction at low temperatures and magnetic fields of up to 15 T, it was shown that DOS between Landau levels increases linearly with the filling factor.

We found the dependence of DOS on the filling factor at room temperature (figure 3), also based on a simple model of the density of states [8]. The dependence demonstrates an increase in the density of states at the Fermi level as a function of the filling factor, i.e. correlates well with the results obtained in [5].

6. Conclusion
In agreement with [5], we believe that the experimentally established behavior of the background DOS, which increases linearly with the filling factor, is due to the contribution of edge states. This conclusion correlates with the existing notion that edge states play a decisive role in the properties of 2DES in the quantum Hall effect mode [11].

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