De Haas-van Alphen effect in a silicon nanosandwich: determination of the effective carrier mass

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Abstract. The field dependence of the magnetization of a silicon nanosandwich at room temperature in low magnetic fields has been analyzed in the framework of the equilibrium thermodynamics formalism. It is shown that the experiment receives an adequate interpretation in the model of de Haas – van Alphen oscillations with an effective carrier mass depending on the external magnetic field.

1. Introduction

Observing quantum magnetic effects at room temperature and in low magnetic fields \([1-3]\) is a serious experimental challenge. Despite this, there has been marked interest in such studies due to the fact that the field dependence of the magnetization of a silicon nanosandwich measured at room temperature (figure 1) demonstrates numerous features significantly different from those obtained when the de Haas-van Alphen effect on two-dimensional structures at low temperatures in strong magnetic fields are studied \([5-8]\). Analysis of the observed features therefore makes it possible to draw important conclusions about the main properties of the studied low-dimensional structure.

In this paper, we present the sample magnetization curve demonstrating the de Haas-van Alphen effect at room temperature, measured in the discrete sweep mode of a magnetic field with a step of \(5\) Oe from \(100\) to \(1100\) Oe. The results were analyzed using equilibrium thermodynamics, which is provided by implementation of a quasistatic process in the course of the measurements. The aim of this work was to analyze the dependence of the effective mass of carriers on the magnitude of the magnetic field in the framework of equilibrium thermodynamics.

2. Experiment

Magnetization measurements were carried out on an MGD 312 FG spectrometer Faraday balance at room temperature in magnetic fields of up to \(1100\) Oe. The Faraday method was used. Samples were placed in the external magnetic field in a quartz cup suspended on a thin quartz filament. The orientation of the sample in the external magnetic field was determined by the geometry of the edge channels, known from previous measurements, and taking into account the recommendations made by Schoenberg \([4]\) regarding the method used. This made it possible to avoid averaging of the magnetic field on the linear size of the structure, which could lead to “blurring” of the oscillations, significantly complicating their observation. The magnetic field was developed in a step-by-step mode with a given value of \(\Delta H\), and the intensity of interaction with the magnetic field was recorded when the sample reached a state of thermodynamic equilibrium, which was controlled by an automated measurement control system using specially developed software. The setup was calibrated using a reference sample.
- a single crystal of magnetically pure indium phosphide with a known susceptibility of \( \chi = -313 \cdot 10^{-9} \text{cm}^3/\text{g} \). The sample mass was determined on a BP 211 D balance with an accuracy of \( 10^{-5} \text{g} \).

Thus, the field dependence obtained in the experiment is a set of discrete values of magnetization reflecting the system behavior in a quasistatic process, that is as it passes through a series of thermodynamically equilibrium states.

The magnetization curve of the sample, obtained by changing the external magnetic field with a step of \( \Delta H = 5 \text{ Oe} \), is shown in figure 1.

3. Experimental results
The dependence of the magnetization on the magnetic field depicted in figure 1 shows well defined de Haas – van Alphen oscillations with integer filling factors up to \( \nu = 8 \), inclusive. Moreover, with an increase in the magnetic field, a decrease in the amplitude of oscillations is observed.

4. Discussion
This report focuses on the experimental dependence of the amplitude of de Haas – van Alphen oscillations on the filling factor, \( \nu \). This allows us to draw conclusions about the patterns of behavior of the effective mass of carriers in a silicon nanosandwich placed in an external magnetic field.

In our analysis, we referred to the results of [5-7], in which experimental and theoretical studies of the de Haas – van Alphen effect were performed in low-dimensional structures at low temperatures and in high magnetic fields, as well as for an idealized system \( (T = 0 \text{ K}) \). Calculations carried out for an idealized system in the study of the energy spectrum of the filled Landau levels [5, 6] showed that
the amplitudes of oscillations are constant for all values of the filling factor. In turn, the results measured at low but finite temperatures, from 0.32 to 6.0 K [7], and calculated at 0.3; 8; 30 K [5], assuming a Gaussian broadening of the Landau levels, demonstrate a monotonic increase in the amplitude of oscillations with increasing magnetic field. This result agrees well with the studies of the de Haas-van Alphen effect on low-dimensional structures with a relatively high effective mass of the carrier (> 10 \( -2 \)) at low temperatures (0.3–30 K) and in high magnetic fields (~ 10 T).

We now turn to the experimental data obtained by observing the de Haas-van Alphen effect on a silicon nanosandwich at room temperature (figure 1). The above dependence demonstrates a decrease in the range of oscillations with increasing intensity of the external magnetic field. It is obvious (figure 1) that the smooth (non-oscillating) component of the magnetization with respect to which oscillations occur is not parallel to the abscissa axis, as is the case on the experimental curves and from the results of theoretical calculations for the de Haas-van Alphen effect observed at low temperatures [5-8].

To visualize this feature, we compared the experimental dependence of the magnetization of the silicon nanosandwich with an idealized curve calculated for the given parameters of the structure under study (figure 2). Based on the preceding, it is obvious that the dependence of the amplitude of the de Haas – van Alphen oscillations on the filling factor observed in our experiment cannot be due to the high temperature of the experiment, but has a different physical nature.

![Figure 2.](image)

**Figure 2.** The superposition of experimental and “idealized” dependencies in the de Haas – van Alphen effect.

At the same time, analyzing the results of the longitudinal conductivity measurements of the sample in an external magnetic field [1] and taking into account the conclusions of [9], to explain the result obtained we assumed the dependence of the effective mass of the carriers in the sample on the applied magnetic field strength.
To qualitatively analyze the behavior of the oscillation amplitude in a system with an effective mass depending on the strength of an external magnetic field, we can again refer to the idealized magnetization curve calculated by differentiating the energy spectrum of the filled Landau levels for a system with a variable carrier mass.

![Graph](image)

**Figure 3.** Superposition of the experimental and “idealized” dependence calculated in the approximation of the variable effective mass in the de Haas – van Alphen effect for a silicon nanosandwich.

The magnetization curve calculated from the energy spectrum of the filled Landau levels at a constant temperature for a system with variable carrier mass shows a decrease in the amplitude of its oscillations with a decrease in the filling factor and displays a nonmonotonic behavior of the non-oscillating (smooth) component of the magnetization curve (figure 3). Thus, the use of an approximate magnetic field-dependent effective mass makes it possible to adequately describe the experiment (figure 3).

Furthermore, the results of the calculations made it possible to determine that in the range of magnetic fields of strength from 100 to 1000 Oe, the effective mass of the carrier monotonously varies from $6 \cdot 10^{-5}$ to $2.4 \cdot 10^{-4}$ the mass of a free electron.

**5. Conclusion**

It was possible to determine the effective mass of carriers, which demonstrate a dependence on the external magnetic field, in the silicon nanosandwich, which is a super-narrow silicon quantum well bounded by δ - barriers heavily doped with boron, by way of the de Haas-van Alphen effect at room temperature and in low magnetic fields. This insight can be used to create modern electronic devices with a control parameter dependent on an external magnetic field.
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