Magnetoresistance Aharonov–Bohm (MAB) oscillations in elongated quantum dots

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Abstract. The type-II InAsSbP ellipsoidal quantum dots (QDs) are nucleated on InAs substrate from In-As-Sb-P quaternary melt-solution using Stranski–Krastanow growth mode. The structures under consideration were prepared in the form of photoconductive cells. Magnetospectroscopy is used to measure the QDs structure's electric sheet resistance in magnetic field at lateral current flow. The magnetoresistance Aharonov–Bohm (MAB) oscillations with the period of $\delta B \approx 0.4$ T are found. No temperature dependence is experimentally revealed for the period of MAB. It is shown the QDs size distribution strongly acts on the period of MAB oscillations. The values for both major and minor semiaxes of ellipsoidal QDs were theoretically calculated using an equation for the period of classical Aharonov-Bohm oscillations. Comparison of calculated and experimentally measured values shows that they are coincide with high accuracy. Additionally, the temperature dependant hysteresis on magnetoresistance curves is revealed.

1. Introduction

Three-dimensional confinement of carriers in a quantum dot (QD) transforms the continuous optical spectrum of a bulk semiconductor into a size-tunable, atomic-like spectrum featuring a series of sharp peaks associated with discrete electronic transitions. These unique electronic and optical properties of QDs have been exploited for a wide range of applications, including quantum electronics and quantum information processing [1, 2], optical communications, display technologies, solar energy harvesting and fluorescent labeling etc. [3]. No classical states of light also can be generated using semiconductor QDs [3-5], enabling on-chip semiconductor quantum optics. Among quantum size objects’ fabrication techniques, when the difference between lattice constants of the growing materials is 3-10%, the self-organized Stranski–Krastanow (S–K) method can be realized, by which dislocation-free nanostructures can be produced [7]. In a strained film, the formation of islands is energetically favorable, as it reduces the strain energy in the crystal [8]. The fabrication and characterization of epitaxially-grown semiconductor QDs had advanced to the point that QD-based devices were realizable. Despite the rapid progress in this field, numerous questions remain with regard to how QD morphology affects the electronic and optical properties and coherent light-matter interactions in semiconductor QDs. The performance of QD-based devices relying on these interactions is typically limited by multiple effects that are still not understood: 1) short coherence and relaxation times due to interactions of the charge carriers with each other and the local environment; 2) sensitivity of the QD
properties on size and confinement; and 3) the presence of many-body interactions that often dominate the linear and nonlinear optical response [3].

In classical mechanics, the electromagnetic potentials ($\varphi$ and $\vec{A}$) first were introduced as a pure mathematical notions for calculating the fields. And the fundamental equations of motion can be expressed only in terms of fields. But in quantum mechanics the equations of motion of a particle are replaced by the Schrodinger equation for a wave, which cannot be expressed in terms of the fields alone, but also requires the electromagnetic potentials [9].

In this paper, actually we are experimentally revealed the magnetoresistance oscillations in InAsSbP type-II QDs due to Aharonov-Bohm effect. Additionally, theoretical calculations of QDs lateral dimensions using the measured period of MAB oscillations are performed.

2. Basic theory

The A-B phase is most simply described as the phase that appears in charged particle’s wave function during its passage through the region where magnetic flux exists, but no effects of classical Lorentz force is present. In semiconductor nanostructures, such as type-II quantum dots or quantum rings, applied magnetic field penetrating the area surrounded by their trajectories will cause a phase shift of the electron-hole pair [9]. At zero magnetic field exciton ground state has zero angular momentum projection ($L=0$), but with increasing magnetic flux its changes to states with higher angular momentum ($L = -1, -2, -3$), causing oscillation of ground state energy of the charge carrier (figure 1c) [11].

Assuming that electron and hole move with different radii and the interaction between them is negligible, in the presence of external magnetic field, the energy of the electron-hole pair will be [9]:

$$E_{exc} = E_g + \frac{\hbar^2}{2m_e R_e^2} (l_e + \frac{\Phi_e}{\Phi_0})^2 + \frac{\hbar^2}{2m_h R_h^2} (l_h - \frac{\Phi_h}{\Phi_0})^2,$$

where $E_g$ includes the band gap and confinement energies and is the magnetic field-independent term, $R_e(h)$ is the rotation radius of the electron (hole), $l_e$ and $l_h$ are the angular momentum (magnetic quantum numbers) of the electron and hole, respectively, $\Phi_0$ is the flux quantum: $\Phi_0 = h/e$ and $\Phi_e$ and $\Phi_h$ magnetic fluxes are equal to $\Phi_e = \pi R_e^2 B$ and $\Phi_h = \pi R_h^2 B$, respectively. Now, taking in account strong Coulomb interaction, when they will rotate together as shown in Fig. 1(b), the exciton spectrum becomes [12]

$$E_{exc} = E_g + \frac{\hbar^2}{2MR_0^2} (L + \frac{\Delta \Phi}{\Phi_0})^2,$$

where $L = l_e + l_h$ is the total momentum of an exciton, $R_0 = (R_h + R_e)/2$, and $M = (m_e R_e^2 + m_h R_h^2)/R_0^2$. Magnetic flux between the trajectories of the particles equals to:

$$\Delta \Phi = \Phi_e - \Phi_h = \pi B (R_e^2 - R_h^2).$$

In case of type-II QDs with strongly confined holes, we can assume that $R_h \rightarrow 0$, therefore $MR_0^2 = m_e R_e^2$ and $\Delta \Phi = \Phi_e$.

In direct-gap semiconductors emission process requires the total angular momentum to be equal 0. Since $l_h = 0$, all ground states of the electron in the conduction band with $l_e = -1, -2, -3...$ states are dark. Hence, the exciton emission from cylindrical type-II QDs in magnetic field will be blocked for $B > B_{AB}$, where $B_{AB}$ corresponds to the field at which the electron ground state energy passes from $l_e = 0$ to $l_e = -1$. However, in real systems due to the presence of defects in QDs, above described mechanism for emission may not take place.
Figure 1. Schematic band structure of type-II QD (a). The sketch of an electron-hole pair in type-II quantum dot (b). The system energy spectra in magnetic field (c).

3. Experimental details
Investigated InAsSbP type-II QDs were grown on industrial undoped n-InAs(100) substrate by liquid phase epitaxy (LPE) using the Stranski–Krastanow growth mode at $T=550\,^\circ C$ constant temperature. The atomic force microscope (AFM «TM Microscopes–Autoprobe CP») and «Keithley-6514 System Electrometer» were used for morphological characterization and magnetospectroscopy, respectively. AFM images of ellipsoidal QDs which are under consideration are presented in figure 2.

Figure 2. AFM images of InAsSbP type-II ellipsoidal QDs in plane (a) and oblique (b) view.

According to the InAs–InSb–InP phase diagram, concentrations of antimony and phosphorus in the growth solution were chosen to provide a lattice mismatch up to 3% between the InAs substrate and
InAsSbP wetting layer at $T=550^\circ$C. Ohmic contacts of the samples were fabricated by the thermal vacuum evaporation technique. The sample’s active surface was chosen to be equal to $10^{-2}$ cm$^2$. Measurements were performed at gradually increasing magnetic field up to 1.6 T with further decreasing up to zero, which was set to be perpendicular to the surface of quantum dots.

4. Results and discussions

Dependence of magnetoresistance on magnetic field measured at Faraday geometry at 300 K is presented in figure 3(a). The dependence of the derivative curve, on which observed effect is more noticeable, is presented in figure 3(b). Observed fractures in this curve, possibly are due to the transitions of charge carriers between energy levels due to the influence of magnetic field. As it was shown in [13], the magnetic flux, evidently, leads to a periodic change in the quantum mechanical properties of the encircling electrons. Therefore, under the influence of perpendicular magnetic field, the electron orbits the QD periphery producing an observable MAB, despite the selection rules for transitions in angular momentum, that are strictly valid only for the situation of perfect rotational symmetry and low temperatures.

![Figure 3.](image)

**Figure 3.** Type-II QDs structure’s resistance versus magnetic field at room temperature (a) and its derivative (b).

From figure 3(b) also one can see, that the period of oscillations equals to $\sim0.38$ T. Interestingly note that the results of measurements performed at liquid nitrogen temperature show the same value for the period of MAB. This result was expected, because the period of Aharonov-Bohm oscillations is given by following equation:

$$\delta B = \frac{\Delta \Phi}{\Phi_0} = \frac{h}{eab}, \quad (4)$$

where $h$ is a Plank constant, $e$ is an elementary charge, $a$ and $b$ are major and minor axles of ellipsoidal quantum dots, respectively, and there is no any temperature dependent parameters. Additionally, AFM measurements show that in our experiments $a=1.23b$. Using equation (4), dependence of the MAB period on ellipsoidal QDs axles was built, which 3D sketch is presented in figure 4.

![Figure 5.](image)

**Figure 5.** Intersection points of $a=1.23b$ line and projection curve of the cross section of 3D graph by $\Phi_0=\delta \Phi$ planes (figure 5(a)) show sizes of ellipsoidal quantum dots, in which the oscillations are take place at respective value of $\delta B$. In figure 5(b) we present intersection point of $a=1.23b$ line and cross section line at $\delta B=0.37T$ from which we can define average sizes of our quantum dots. On the other hand, for each ellipse we can find corresponding circle with the same surface area. In our case the radii of corresponding circle is equal to 59.7 nm (black curve) and for major and minor semiaxis 66 nm and 54 nm, respectively. At the same time, infinite number of ellipses correspondence to that line.
Figure 4. Dependence of MAB oscillations period on ellipsoidal QDs axles.

Figure 5. Cross sections of 3D graph by $\delta B = \text{const} - (a)$ and $\delta B = 0.37T - (b)$ planes.

Oblique view AFM images of single QDs grown from In-As-Sb-P quaternary liquid phase on InAs(100) substrate are presented in figure 6, from which one can see that the growth process and technological conditions result in an elongation of QDs in certain direction.

Comparing theoretically obtained values for quantum dots' sizes with experimentally measured values, it is not difficult to see, that they are coincide with high accuracy. This fact allows us to precisely define the size of cylindrical quantum dots in which MAB has occurred. As for ellipsoidal quantum dots, we only need to know the relation between values of semiaxes.
5. Conclusions

Thus, Aharonov-Bohm oscillations with the period of $\delta B \approx 0.4$ T were found on the curve of the magnetoresistance derivative at room temperature. The average values for both major and minor semiaxes of ellipsoidal QDs were theoretically calculated by the equation for the period of Aharonov-Bohm oscillations. Comparison of calculated and experimentally measured values shows that they are coincide with high accuracy.

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Figure 6. AFM images of QDs grown on InAs(100) substrate.