Spin-Landau Orbit Coupling in Units of the Flux Quantum Observed from Zeeman Splitting of a Quantum Wire Array

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In Zeeman spectra of a GaAs-AlGaAs quantum wire array with superlattice period $l_p$, the zero-field shift is found to increase in steps of $(2\pi\hbar/e)l_p^{-2}$ at the cyclotron radius $R_c \approx l_p, l_p/2, \text{and } l_p/3$. This shift, caused by spin-Landau orbit coupling and quantized in units of the flux quantum $2\pi\hbar/e$, is a manifestation of the gauge invariance, and the first observation of the flux quantization in a non-superconducting material. The quantum interference associated with the phase difference in the quantum barrier scattering is also reported.

71.70.Ej, 78.66.-w, 73.20.Dx, 78.20.Ls

The electronic properties of one-dimensional (1D) quantum structures attract particular interest. However, most of the studies of 1D confinement are limited to investigations of transport [1,2] and optical properties [3–5], and little is known about 1D quantum confinement on the electronic spin state. In this letter, we report experimental results on the Zeeman splitting of a quasi-1D confined electron system, namely a quantum wire (QWR) array. In this system, the electronic motion is influenced by three characteristic physical lengths: radius $R_c$ of the Landau orbit, periodic length $l_p$ of the quantum wire superlattice, and exciton diameter. The results show that the spin of the electron confined in a 1D periodic potential is coupled with the Landau orbital motion - this is observed as the zero-field splitting increases in steps for the applied field. The internal field produced by the Landau orbital motion gives the flux per $l_p^2$ quantized in units of the flux quantum $2\pi\hbar/e$, which is characterized by $R_c$ and $l_p$ from the Landau gauge magnetic translation (LGMT).

The Zeeman spectra are obtained from polarization dependent magneto-photoluminescence (PMPL) in a GaAs/Al$_{0.5}$Ga$_{0.5}$As QWR array sample. The sample was grown using our Riber MBE system by migration enhanced epitaxy on vicinal GaAs surfaces of 1° off from (001) plane [6,7]. The growth of GaAs and AlGaAs layers were switched every 1/2 monolayer, and repeated for 30 periods. The structure thus consists of GaAs QWR of 30 molecules in width and height with AlGaAs barriers of 30 molecules between the wires, providing the superlattice period $l_p \approx 170$ Å. The PMPL is detected using $\pi/2$ circular polarizer, while applying dc magnetic field perpendicular to the array plane. The PMPL at 4.2 K

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is obtained in steps of 1 T up to 32 T with a resolution of \( \leq 0.05 \) meV. The spin up and down components of the Zeeman splittings are obtained by reversing the field direction. The TEM image of this sample and schematic diagram of the array structure with respect to the applied field are shown in Fig. 1 (a) and (b), respectively.

The PMPL peak positions \( E_+ \) and \( E_- \), which correspond to spin up and down components respectively, are shown with ▲ and ▼ symbols in Fig. 2. The solid line indicates the average of \( E_+ \) and \( E_- \), which corresponds to the conventional diamagnetic and Landau shift. The PMPL peak at zero field is observed at a photon energy of 1942.5 meV. A typical PMPL linewidth (FWHM) is 12 meV at low field and gradually decreases to 10 meV at high field.

The data obtained at high fields are compared with the dispersion of the lowest sublevel of the 2D electron system,

\[
E_{\lambda \pm} = E_0 + \left( \lambda + \frac{1}{2} \right) \frac{\hbar e B_a}{m^*} \pm \frac{1}{2} g_{eff} \mu_B \mu_B, \quad (1)
\]

where \(+\) and \(-\) denote the electronic spin up and down states, \( E_0 \) the lowest level energy, \( \lambda(= 0, 1, 2, \cdots) \) the Landau level index, \( \omega_c = eB_a/m^* \) the cyclotron frequency, \( \mu_B = e\hbar/2m_e \), \( g_{eff} \) the effective g-factor, \( m^* \) the reduced effective mass, and \( m_e \) the free electron mass. From the slope of \( E_{\lambda,ave} = (E_\lambda^+ + E_\lambda^-)/2 \) for \( B_a > 10 \) T, \( m^* = (0.145 \pm 0.003)m_e \) is obtained.

Zeeman splitting is obtained from the separation of the spin up and down states, \( \Delta E = E_+ - E_- \), and is summarized in Fig. 3. Our results at \( B_a \geq 4 \) T show that only the electron spin in the ground sublevel contributes to the Zeeman splitting with little excitonic effect. The microwave measurement has also reported that the electronic spin state is hardly affected by the holes in an undoped quantum well (QW) \[8,9\]. Unlike 2D cases, the Zeeman splitting of the ground-state electron can be fit to a single line of \( \sim g_{eff} \mu_B B_a \), our Zeeman data cannot be fit to a single line of \( g_{eff} \mu_B B_a \). Using the value \( g_{eff} = -0.44 \) which is the g-value of GaAs bulk and undoped GaAs QW \[10\], the data for \( B_a \geq 4 \) T fit rather well with three straight lines, in the form

\[
\Delta E = g_{eff} \mu_B B_a + \Xi. \quad (2)
\]

The best fit values of \( \Xi \) are 0.85 meV for \( 4 \) T \( \leq B_a \leq 8 \) T and 1.70 meV for \( 9 \) T \( \leq B_a \leq 15 \) T. For \( B_a \geq 16 \) T, the six data points at \( B_a = 16, 17, 20, 21, 24, \) and 25 T, which are the peaks of the oscillation existing in this region, are used for the fit and \( \Xi \) is found to be 2.50 meV. (See solid lines in Fig. 3) The above three regions are referred to as Regions 1, 2, and 3, respectively. For these three regions, the Zeeman separation in Eq. (2) can be rewritten as

\[
\Delta E_n = g_{eff} \mu_B B_a + n\Xi \quad (3)
\]
with $X = 0.85 \pm 0.02$ meV and $n = 1, 2, \text{ and } 3$. The shift $\Xi$ and thus $nX$ in Eq. (3) are mathematically equivalent to a zero-field shift in magnetic resonance, and the Zeeman energy $Z$ can be understood in terms of the internal magnetic field $B_i$:

$$Z = \mu_B s \cdot B_i, \tag{4}$$

where $s$ is the electron spin operator. Since the only source for the internal field is the cyclotron motion of the electron, it is natural to attribute the zero-field shift to the spin-Landau orbit coupling, which is similar to the $\mathbf{L} \cdot \mathbf{s}$ coupling in an atom. The separation between the spin up and down states coupled with the internal field $B_i = B_i \hat{z}$ becomes

$$\Delta Z = \mu_B (s_\uparrow - s_\downarrow) \cdot B_i = \mu_B B_i \equiv n \mu_B B_1. \tag{5}$$

When our experimental value of $X = 0.85 \pm 0.02$ meV is substituted for $\mu_B B_1$ in Eq. (5), it is found that

$$B_1 = 15.6 \pm 0.4 \text{T.} \tag{6}$$

To explain this quantized shift, we consider a 2D electron in a magnetic field. In the Landau gauge $\mathbf{A} = \hat{x}(-y)B$, the wavefunction at the ground-state Landau level is given by

$$\Psi_{k_x} \equiv \langle x, y | \lambda = 0, k_x \rangle = \exp(ik_x x) \exp \left[ -\frac{m^* \omega_c}{2\hbar} \left( y - \frac{\hbar k_x}{m^* \omega_c} \right)^2 \right]. \tag{7}$$

If we introduce an over-simplified 1D potential of our QWR superlattice $U(y) = U_0 \cos(2\pi y/l_p)$, we can see that $\langle k_{x'} | U | k_x \rangle = U_0 \exp(-\pi/2f) \cos(k_{x'} l_p/f) \delta_{k_{x'},k_x}$ is diagonalized with $f \equiv eB_1 l_p^2/(2\pi \hbar)$. Comparing with the Harper equation on a 2D square lattice [11], this shows that

$$k_x = \frac{2\pi n}{l_p} \tag{8}$$

is a good quantum number, which is well-defined along the $x$ direction. Through the use of Eq. (5), the expectation value of the $z$-component of the angular momentum is obtained as

$$\langle L_z \rangle = \int \int \Psi_{k_x}^* \left[ -i\hbar \left( x \frac{\partial}{\partial y} - y \frac{\partial}{\partial x} \right) \right] \Psi_{k_x} \, dx \, dy$$

$$= \int \int \Psi_{k_x}^* \left[ \hbar k_x y - im^* \omega_c x \left( y - \frac{\hbar k_x}{m^* \omega_c} \right) \right] \Psi_{k_x} \, dx \, dy$$

$$= \frac{\hbar^2}{m^* \omega_c} k_x^2 \tag{9}$$

A precise calculation of the effective field produced by the cyclotron motion of the electron in this system and coupled with the spin contributing the zero-field shift may
require many-body consideration. However, for an approximate computation, let us assume that the spin coupling is dominated by the field near the orbit. Then, this field can be obtained via the semi-classical approach to obtain the field

\[ B_{\text{eff}} = \frac{m^*v}{el_p} = \frac{eB_a \langle L_z \rangle}{el_p} = \frac{2\pi \hbar}{el_p^2} n \]  

(10)

where Eq. (8) and (9) have been used. This shows that the flux passing through the area defined by the 1D period

\[ \Phi = B_{\text{eff}} l_p^2 = \frac{2\pi \hbar}{e} n \]  

(11)

may indeed be quantized in units of the integer flux quantum \(2\pi \hbar/e\).

Hofstadter has investigated the commensurability effects associated with the field in units of the flux quantum by applying the LGMT invariance to Bloch band calculations [11]. However, this calculation is based on a 2D periodic potential and considers the flux defined by the periodic spacing along both \(x\) and \(y\) directions. In our case, even though the QWR array has only one periodic length along the \(y\) direction, the rotational symmetry in the LGMT brings the additional characteristic length along the \(x\) direction.

Now let us compute the flux \(B_l\) passing through the square \(l_p^2\). By substituting our experimental values of \(B_l = B_{\text{eff}}\) and \(l_p = 170\ \text{Å}\) into Eq. (11), we obtain for \(n = 1\)

\[ \Phi_{\text{exp}} = B_l l_p^2 = (4.3 \pm 0.1) \times 10^{-15} \text{T} \cdot \text{m}^2. \]  

(12)

This value coincides with the quantity

\[ \Phi_1 = \frac{2\pi \hbar}{e} = 4.13 \times 10^{-15} \text{T} \cdot \text{m}^2 \]  

(13)

with the error of \(\leq 5\%\).

The oscillatory behavior of the Zeeman shift is apparent at \(B_a \geq 16\ \text{T}\). (See the broken line in Fig. 3 which is 3 points averaging) The period of this oscillation is found to be approximately \(\Delta B_a = 4.7\ \text{T}\) from the peaks indicated with arrows in Fig. 3. This oscillatory behavior has similarity with the quantum oscillation reported in magneto-transport measurements \[12,13\] and the energy level calculation \[9,10\], which is characteristic of the 1D periodic potential. However, the oscillatory behavior of our Zeeman splitting and the Landau-band conductivity are different; one is periodic with \(B_a\) and the other with \(1/B_a\).

This Zeeman oscillation is also a quantum oscillation caused by 1D periodicity, but it differs in nature. Since the scattering conditions are different at points P and Q of the heterointerface, these two orbits have different phase factors (See Fig. 3). This phase difference in consequence gives the quantum interference effect to the net effective field (observe the differences of the solid-line path
and dot line path reflected by quantum barrier (QB) in Fig. 4, and the period of the interference is obtained as $l_p^2 e \Delta B \hbar = 2 \pi n$. The oscillation period of $\Delta B_a = 4.7 \; T$ observed for $n = 3$ matches well with $1/3$ of $B_1$. The constructive interference would occur at the applied field corresponding to $\alpha \equiv l_p / R_c = 3$, where $R_c = \sqrt{\hbar / (e B_a)}$, and those separated by $\Delta B_a$ from that point. This is the reason why we have chosen the six peaks in Zeeman separation, when we fit the data for $n = 3$. The reason why the transition to Region 3 occurs around $\alpha = 2.6$ rather than $\alpha = 3$ is not clear. It may merely be due to an experimental error introduced by the fluctuation of QWR array period, or may be related to the interference effect. The details on the quantum interference effect is out of the scope of this paper and will be reported elsewhere.

Another feature of interest is the values of $B_a$ where the step-like transitions take place. They occur at $\alpha = 1, 2,$ and $\approx 3$ for the transitions to Region 1, 2 and 3, respectively. The transition occurring at $n = \alpha$ means that the number of the flux quantum, $n$, is the maximum number of the Landau orbit which can be linearly placed in the stripe of the length $l_p$. This also implies that the propagation of the electron reflected by QB is modulated along the QWR with the period of $l_p$. This picture is consistent with Eq. (8).

In conclusion, we have performed polarization dependent magneto-photoluminescence on a GaAs/Al$_{0.5}$Ga$_{0.5}$As QWR array sample and have observed that the Zeeman separation increases in steps at fields corresponding to $\alpha = 1, 2,$ and $\approx 3$. The step-like shift is the result of the spin coupling to the Landau field, the field produced by the Landau orbital motion, and provides the clear indication that the Landau field is manifested at $B_i = n \Phi_1 l_p^{-2}$ in units of the flux quantum $\Phi_1 = 2 \pi \hbar / e$. It is the rotational symmetry of the Landau orbit in conjunction with the linear translational invariance that gives the additional dimensional confinement; this yields effectively the 2D confinement condition similar to Hofstadter’s. Also observed along with the step-like shift in the Zeeman splitting is the oscillatory behavior which is apparent at $R_c \lesssim l_p / 3$. The Zeeman oscillation is due to the quantum interference caused by the rotational phase difference of Landau orbits in QB scattering. Both the Landau orbital field quantization and the quantum oscillation are collective phenomena characterized by the 1D confinement and periodicity presented by QWR array. The flux quantization observed in this well-fabricated QWR array provides a clear indication that a single electron in the Landau orbital path produces a long-range quantum effect in which the coherence of the 1D confinement extends over a solenoid defined by the superlattice period. We believe that this work provides the direct and convincing evidence for the magnetic flux quantum in non-superconducting material.

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FIG. 1. (a) TEM image of the QWR sample. (b) Schematic diagram of the experimental condition.

FIG. 2. The applied field dependence of peak positions of polarization dependent magneto-photoluminescence spectra. The symbols, ▲ and ▼, are for the spin-up and down states, respectively, and the solid line shows the average between the two.

FIG. 3. The field dependence of Zeeman separation. The solid lines are the best fit curves for the corresponding regions. The arrows point to peaks in the oscillation maxima, and \( \alpha = l_p/R_c \) is marked along x-axis.

FIG. 4. Schematic diagram of two cyclotron paths which have different scattering conditions. It also schematically shows the path (dot line) reflected at QB may present the quantum interference effect with a cyclotron path (solid line).
Zeeman Splitting (meV) vs. Magnetic Field (Tesla). The graph shows three distinct curves labeled $n=1$, $n=2$, and $n=3$. The curves are linear and illustrate the splitting of energy levels with increasing magnetic field. The data points indicate the progression of splitting with field strength.
