LANDAU LEVEL QUANTIZATION AND SUPERCONDUCTIVITY*

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Submitted to 33rd Yamada Conference on the Application of High Magnetic Fields in Semiconductor Physics, Chiba, Japan, August 3-7, 1992.

*Work Supported by the U.S. Department of Energy, BES-Materials Sciences, under Contract #W-31-109-ENG-38.

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ABSTRACT:

A microscopic calculation of vortex-lattice states in two-dimensional electron systems at strong magnetic fields is made taking fully the Landau level quantization into account within the mean field scheme. Results of the order parameter and the local density of states are presented both in the limit of pairing in a single Landau level and in the semiclassical regime of weaker fields and differences from the Abrikosov vortex state are discussed.

Keywords : superconductivity, magnetic field, Landau level, vortex lattice, electron tunneling

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The importance of the Landau level quantization in the superconducting phase has been attracting much attention, since the de Haas-van Alphen oscillations were observed in the vortex phase of the type-II superconductors such as the layered dichalcogenide 2H-NbSe₂ [1, 2] and the high-temperature superconductor YBa₂Cu₃O_{6.97} [3, 4]. Although the commonly-used Ginzburg-Landau theory was successfully employed by Abrikosov [5] to discuss the vortex-lattice state, it is restricted to the weak-field region where effects of the Landau level quantization can be neglected. Theories beyond this semiclassical approximation were mainly on the transition temperature T_{c2} [6, 7] and it was clarified that there is a new region above the semiclassical critical field H_{c2} in which T_{c2} increases with the magnetic field [8]. This is understood by the increase of the effective density of states at the Landau level. Quite recently, the nature of the vortex state in such a strong magnetic field has been studied by us [9, 10, 11] and other groups [12, 13]. In this paper we employ a quantum theory [9,10,11] of the vortex-lattice state in two-dimensional superconductors within the mean-field scheme, and calculate the order parameter and the local density of states. The latter is easily accessible experimentally by the scanning tunneling microscope (STM).

The mean-field BCS theory is extended to pairings in Landau levels. The BCS model of attractive interactions is used: the delta-function interactions $-V\delta(\mathbf{r})$ ($V > 0$) act between electrons whose energies are within the cut-off frequency Ω_c of the chemical potential. Assuming a periodicity of the order parameter and using the magnetic Bloch function, which is a linear combination of the Landau wavefunction, the Hamiltonian is shown to be diagonal in the crystal momentum $\mathbf{k}$ and the Cooper pair is formed between

states with $\mathbf{k}$ and $-\mathbf{k}$. To evaluate the pairing term, it is important to note that the quantized kinetic energy of the center-of-mass motion is conserved in scattering events between two electrons interacting via a force which depends only on relative coordinates. Therefore the conserved Landau index (j) for the center-of-mass motion defines different channels of pairing. The order parameter in a position representation is a sum of contributions from different j and can be written as

$$\Delta(\mathbf{r}) \propto \sum_j (-1)^j \Delta_j f_j(\mathbf{r}), \quad (1)$$

with

$$f_j(\mathbf{r}) = \sum_t e^{i\pi t^2/2} \phi_{j,\sqrt{2}t\mathbf{a}_x}(\sqrt{2}\mathbf{r}), \quad (2)$$

and Δ_j is the weight of the j th channel which is to be calculated self-consistently. The sum over j runs from 0 to $2N_{\text{max}}$ when electrons in Landau levels up to N_{max} are participating the pairing. The Abrikosov vortex state corresponds to $j = 0$. The t -sum is over all integers and $\phi_{N,X}$ is the Landau wavefunction for the state with a guiding center X in the N th Landau level in the Landau gauge. Two translation vectors of the lattice of $\Delta(\mathbf{r})$ are $(a_x, a_y/2)$ and $(0, a_y)$ with $a_x a_y = \pi l^2$ and $l^2 = \hbar c / eB$. In the following, the Zeeman splitting, which suppresses T_{c2} , is neglected. Doped semiconductors with small effective mass (thus small effective g -factor) are a promising candidate for the reentrant superconductivity.

First we present results in the quantum limit, in which electrons in a single Landau level (N) participate the pairing. In the quantum limit, the highest T_{c2} appears at both the minimum and the maximum of j , that is, $j = 0$ and $j = 2N$, and is plotted in fig.1 as a function of the filling factor ν of the Landau levels, which is proportional to the inverse magnetic

field because the number of electrons is fixed. This is in contrast to the semiclassical case in which T_{c2} is a decreasing function of j . This important difference suggests a new vortex state in the quantum limit. In fact, the self-consistent mean-field solution shows that the order parameter is not of $j = 0$ character but completely different from the Abrikosov phase, except in the lowest Landau level ($N = 0$) where the only possible j is 0. For example, the contour plot of the order parameter is shown in fig.2 for the triangular lattice in $N = 1$ ($\nu = 3$) at $T = 0$, in which the order parameter is of pure $j = 2$ character. There are three vortices in a unit cell: two with vorticity +1 and one with vorticity -1. By changing the aspect ratio $R = 2a_x/a_y$, it is shown that the total energy is lower in the triangular lattice ($R = \sqrt{3}$) than in the square lattice ($R = 1$) but the ground state is at $R = 5.42$ within the assumed lattice symmetry and its order parameter is a mixture of $j = 0$ and $j = 2$. In the quantum limit there are some more features different from the semiclassical region. (1) When the chemical potential is at a Landau level (ν is an odd integer), the current density is exactly zero (no Meissner effect) and the energy gap of quasi-particles is zero at a point of the magnetic Brillouin zone ($\pi/a_x \times \pi/a_y$). (2) No uniform current is induced in the absence of Landau-level mixings. (3) The local density of states has only a weak dependence on the position in both $N = 0$ and $N = 1$ in contrast to the semiclassical case shown below.

In the weak-magnetic-field region with mixings of Landau levels, results approach those in the Abrikosov vortex state, which corresponds to $j = 0$. Calculated results of the order parameter and the STM tunneling conductance, which is proportional to the local density of states, are presented in fig.3 for $T = 0$ and in fig.4 for $T = \hbar\omega_c/k_B$ in the triangular lattice. The

BCS coupling constant $\lambda = V/(2\pi l^2 \hbar \omega_c)$ is 1. The chemical potential is at $N = 20$ and Landau levels from $N = 10$ to 30 are involved in pairing, corresponding to a field about 0.38 times the semiclassical $H_{c2}(0)$. The profile of tunneling conductance at moderate temperatures is similar to the experiment [14] and the isolated vortex calculation [15]. There are two main differences. (1) The zero-bias peak originating from the bound state shifts to the higher bias. (2) Even at the point between vortices the tunneling conductance is appreciable around the zero bias due to the extended nature of the quasiparticle state.

The crossover from the peculiar state in the quantum limit to the Abrikosov state is observed by decreasing the magnetic field or by increasing the BCS coupling constant λ [11]. In the crossover regime above the semiclassical $H_{c2}(0)$, the order parameter is mainly of $j = 0$ character at $T = 0$, but there are many local energy minima as a function of the aspect ratio and the triangular lattice is not the lowest-energy solution.

This work was supported in part by the DOE, Basic Energy Sciences, under Contract No. W-31-109-ENG-38, and in part by the Midwest Superconductivity Consortium through DOE Grant No. DE-FG-02-90ER45247.

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FIGURE CAPTIONS

Fig.1. Transition temperature T_{c2} as a function of the filling factor ν at a fixed electron density. ν is proportional to $1/B$.

Fig.2. Contour plot of the absolute value of the order parameter in the triangular lattice at $T = 0$ at a strong field with $\nu = 3$. The absolute value is smaller in a darker region. The box sides are a_x (horizontal) and a_y (vertical).

Fig.3. Tunneling conductance and the order parameter in the semiclassical region at $T = 0$. Six curves (shifted successively by 10) are for different points between a vortex center (top curve) and an interstitial (bottom curve) along the line in the figure of the order parameter.

Fig.4. Tunneling conductance and the order parameter in the semiclassical region at $T = \hbar\omega_c/k_B$. Each curve is successively shifted by 1.

Fig. 1

Fig. 2

Fig 3

$T = 0$

$$T = \hbar\omega_c / k_B$$

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