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LANDAU LEVEL BROADENING AND VAN HOVE SINGULARITIES IN LATERAL SURFACE SUPERLATTICES

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A lateral periodic submicrometer potential in one direction superimposed on a two-dimensional electron gas (2DEG) lifts the degeneracy of the Landau levels (LL's) and leads to modulation broadened Landau bands. Due to the new band structure, singularities in the density of states (DOS) are expected which should result in a double peaked structure of the LL's (Van Hove singularities). Increasing the modulation amplitude of the periodic potential we observe a splitting of the Shubnikov–de Haas (SdH) maxima in magnetoresistance measurements which we believe to be the first observation of van Hove singularities in such modulated systems. In addition we report magnetotransport experiments in a weak two-dimensional periodic potential.

1. Introduction

In two-dimensional electron systems with a one-dimensional periodic modulation in the x-direction, a novel oscillatory behavior of the magnetoresistance dominates the low field regime as long as the elastic mean free path of the electrons is large compared to the period a of the periodic potential [1–3]. The modulation with periods a around 300 nm can be realized by holographic illumination using the persistent photoconductivity effect in GaAs–AlGaAs heterojunctions [1,4]. In addition to the usual Shubnikov–de Haas (SdH) oscillations at larger values of the magnetic field we found pronounced low field oscillations of the resistivity ρ_{xx} relating the components of electric field and current in the direction of the modulation, whereas ρ_{yy} showed only much weaker oscillations with a phase shift of 180° with respect to those of ρ_{xx}. Similar to the SdH oscillations, which below 1 T are superimposed on the novel low field oscillations, these new oscillations are periodic in $1/B$, where the minima of ρ_{xx} can be characterized by the commensurability condition [1]

$$2R_c = (\lambda - \tfrac{1}{4})a, \quad \lambda = 1,2,3..., \tag{1}$$

between the cyclotron diameter at the Fermi level, $2R_c$, and the period a of the modulation. Theoretically [2,3], these experimental findings have been explained by a modified Landau energy spectrum (in first order perturbation theory)

$$E_n(x_0) = (n + \tfrac{1}{2})\hbar\omega_c + \langle nx_0 | V(x) | nx_0 \rangle, \tag{2}$$

where $|nx_0\rangle$ stands for the wavefunctions of the unmodulated 2DEG (with a spatial extent of about $2R_c$ in the x-direction), n is the LL index, and $V(x)$ the superimposed potential $V(x) = V_0 \cos Kx$ ($V_0 \ll E_F$, the Fermi energy, $K = 2\pi/a$). A typical energy spectrum together with the corresponding DOS is plotted in fig. 1. As a consequence of the periodic potential the LL width oscillates with n which results in an oscillation of the DOS maxima. Singularities in the DOS occur when $dE_n(x_0)/dx_0 = 0$, resulting in a double peak structure as is sketched in fig. 1. In a real physical system the bands are additionally collision broadened and characterized by a linewidth Γ. The dispersion of the Landau bands with respect to

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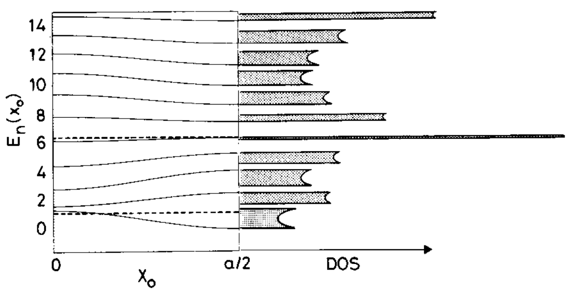

Fig. 1. Calculated energy spectrum (first order perturbation theory) for $B=0.8$ T, $V_0=1.5$ meV and $a=100$ nm [2]. The corresponding DOS is sketched. Flat parts of $E_n(x_0)$ lead to singularities in the DOS. The dashed lines correspond to the flat band situation determined by eq. (1).

the center coordinate x_0 leads to an additional conductivity contribution $\Delta\sigma_{yy}$(and therefore an additional contribution to ρ_{xx}) which vanishes when the bands become flat (minima in ρ_{xx}). This flat band situation is obtained when $\langle nx_0|V(x)|nx_0\rangle$ at the Fermi level vanishes, which is the case when eq. (1) is satisfied. The wavefunctions then effectively average out the periodic potential over an interval of the order of the cyclotron diameter $2R_c$ [2]. The additional minima in ρ_{xx} are therefore obtained when the DOS at the Fermi energy has a maximum. Within the constant relaxation time approximation which has been used to explain the novel oscillations no extra structure appears in ρ_{yy} [2,3,6]. Going beyond this approximation, Gerhardts and Zhang have shown that an oscillatory scattering rate which reflects the quantum oscillations of the DOS causes the oscillations in ρ_{yy} [5].

2. DOS and Van Hove singularities

The thermodynamic density of states is directly reflected in magnetocapacitance measurements [8,9]. The experiments have been carried out using conventionally grown AlGaAs–GaAs heterostructures after holographic illumination [7]. We have used a Hall bar geometry (sketched in fig. 2) where the active region is covered by an 8 nm thick semi-transparent NiCr film as a gate electrode. Such a transparent gate allows capacitance measurements as well as the variation of the carrier density N_s after holo-

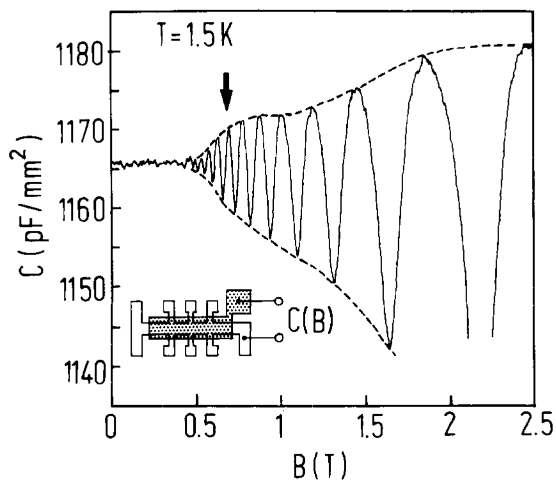

Fig. 2. Magnetocapacitance of a holographically modulated ($a=365$ nm) sample with $N_s=3.2\times10^{11}$ cm^{-2} and mobility $\mu=450\,000$ cm^2/V·s which corresponds to a mean free path of about 4μm.

graphic illumination. The magnetocapacitance – measured between gate and 2DEG – oscillates with B due to the Landau quantization and the capacitance maxima are directly connected to the DOS maxima [8,9]. Magnetocapacitance data from a modulated 2DEG with $a=365$ nm are shown in fig. 2. The oscillating LL width is reflected by the modulation of the envelope of the capacitance oscillations (dashed lines in fig. 2). At about 0.69 T (marked by an arrow) where the cyclotron diameter equals three quarter of the period a ($\lambda=1$ in eq. (1)) the last flat band is swept through the Fermi energy. If now the magnetic field is further increased, broader Landau bands are swept through the Fermi level and cause the modulation (fig. 2) of the capacitance maxima which directly reflect the maximum DOS at the Fermi level. At higher magnetic fields the level broadening saturates and the usual LL degeneracy again raises the DOS in a LL with increasing field. This experiments have been compared to calculations of the DOS in modulated systems which support the picture given above more quantitatively [7]. The experiment above has given proof of the oscillating LL width, however, the van Hove singularities sketched in fig. 1 are not resolved in the experiment suggesting that the collision broadening dominates. We have performed magnetoresistance measurements where we have applied a negative voltage between the semi-transparent gate and the 2DEG after holographic illumination ($a = 282$ nm). The ρ_{xx} data at different gate voltages are plotted in fig. 3 where the SdH-maxima corresponding to the LL's $n = 1$ are hatched. Increasing the gate voltage V_g from −200 mV to −300 mV increases significantly the amplitude of the periodic potential induced oscillations at low magnetic fields. One can estimate from the amplitudes (see e.g. ref. [3]) at about 0.5 T that V_g has been increased from 0.3 meV to about 0.9 meV at $V_g = -300$ mV. The enhanced modulation seems to be due to a redistribution of charge in the doped AlGaAs layer since the carrier density does not change significantly when V_g is increased from −200 mV to −300 mV, as can be seen from the position of the SdH-minima. The increase of V_0 is accompanied by a clear splitting of the $n = 1$ SdH-maximum at $V_g = -300$ mV. On the other hand, the spin splitting at filling factor $\nu = 3$ is only poorly resolved at $V_g = 0$ so that we rule out simply observing spin splitting at −300 mV since we have reduced the mobility from about 400 000 $cm^2/V \cdot s$ at $V_g = 0$ to 200 000 $cm^2/V \cdot s$ at $V_g = -300$ mV. Usually one expects a reduced effective g-factor and therefore reduced spin splitting at lower mobilities due to an increased collision broadening of the LL's [10]. The observed pronounced splitting of the $n = 1$ maxima is only observable in connection with an increase of V_0 and not present after holographic illuminations producing a lower modulation amplitude. Therefore we believe that the observed splitting of the SdH-maxima is the first observation of Van Hove singularities in such modulated systems. This additional splitting is no longer resolved at $V_g = -410$ mV suggesting that the collision broadening now again dominates the modulation broadening. Similar magnetoresistance measurements should be extended to ρ_{yy} since the effects due to the singularities in the DOS should there be even more pronounced [11].

3. Magnetoresistance in a two-dimensional periodic potential

In the last section we present some preliminary results of low field magnetotransport in a two-dimensional periodic potential. In such a potential grid the commensurability problem becomes more severe as compared to the 1D case and results in a complicated energy spectrum [12], and the shape of the DOS is not clear. The two-dimensional periodic potential ($V_0 \ll E_F$) with $a = 365$ nm is created by successively illuminating holographically a high mobil-

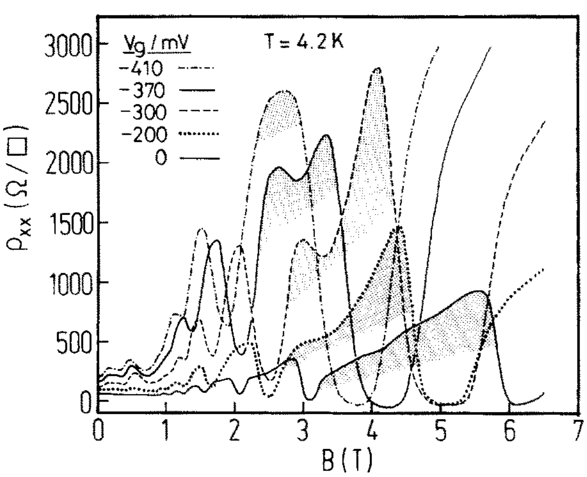

Fig. 3. ρ_{xx} versus B at different gate voltages. The hatched regions correspond to SdH maxima with LL index $n = 1$. The data are taken after holographic illumination producing a periodic modulation with $a = 282$ nm.

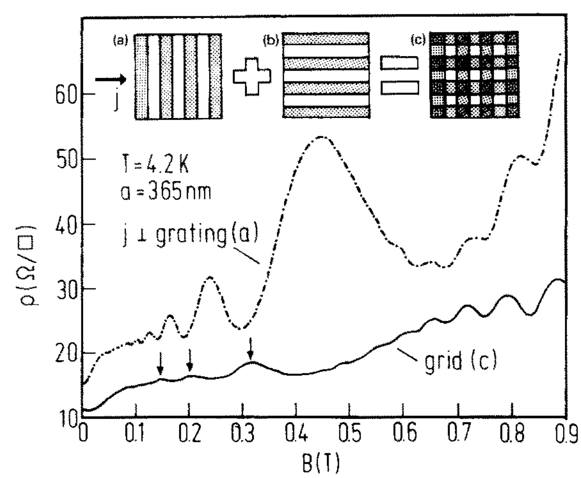

Fig. 4. Magnetoresistance in a grating ($j \perp$ grating) and grid. The creation of the holographically defined pattern is shown schematically.

ity ($\mu=1.2\times10^6$ $cm^2/V\cdot s$) heterostructure. Holographic illumination of type (a) in fig. 4 produces additional oscillations in the magnetoresistance (ρ_{xx} dash-dotted line in fig. 4). An additional holographic illumination where the sample has been rotated by 90° results then in a grid potential sketched in fig. 4c. The magnetoresistance obtained under such conditions (solid line in fig. 4) displays a weak oscillating behaviour with maxima where ρ_{xx} shows minima. If one starts with an illumination of type (b) followed by (a) one ends up with the same result. The result we obtain for the magnetoresistance in a two-dimensional periodic potential is therefore very close to the result one gets when the current flows parallel to a potential grating (maxima in ρ when eq. (1) is fulfilled), discussed as additional oscillations in ρ_{yy} above. Therefore we speculate that the DOS in a weak grid potential is similar to those in a grating [7] and that the oscillating magnetoresistance (apart from SdH-oscillations) in a two-dimensional potential also reflects the oscillating scattering rate due to corresponding oscillations in the DOS.

References

[1] D. Weiss, K. von Klitzing, K. Ploog and G. Weimann, Europhys. Lett. 8 (1989) 179.

[2] R.R. Gerhardts, D. Weiss and K. von Klitzing, Phys. Rev. Lett. 62 (1989) 1173.

[3] R.W. Winkler, J.P. Kotthaus and K. Ploog, Phys. Rev. Lett. 62 (1989)1177.

[4] K. Tsubaki, H. Sakaki, J. Yoshino and Y. Sekiguchi, Appl. Phys. Lett. 45 (1984) 663.

[5] R.R. Gerhardts and C. Zhang, Surf. Sci. 229 (1990) 92.

[6] C.W.J. Beenakker, Phys. Rev. Lett. 62 (1989) 2020.

[7] D. Weiss, C. Zhang, R.R. Gerhardts, K. von Klitzing and G. Weimann, Phys. Rev. B 39 (1989) 13020.

[8] T.P. Smith, B.B. Goldberg, P.J. Stiles and M. Heiblum, Phys. Rev. B 32 (1985) 2696.

[9] V. Mosser, D. Weiss, K. von Klitzing, K. Ploog and G. Weimann, Solid State Commun. 58 (1986) 5.

[10] Th. Englert, D.C. Tsui, A.C. Gossard and Ch. Uihlein, Surf. Sci. 113 (1986) 295.

[11] G.R. Aizin and V.A. Volkov, Sov. Phys. JETP 60 (1984) 844.

[12] D.R. Hofstadter, Phys. Rev. B 14 (1976) 2239.