MAGNETIC BREAKDOWN IN 2D HOLE SYSTEM AT GaAs/$Al_{0.5}Ga_{0.5}As$ HETEROINTERFACE

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The magnetic breakdown development under uniaxial stress has been detected for the first time in 2D hole gas at p-GaAs/$Al_{0.5}Ga_{0.5}As$ heterointerface and indicates the specific character of the FS transformation.

1. Introduction

Phenomenon of magnetic breakdown (MB) represents the most explicit demonstration of a quantum character of electron and hole motion in solids. It is understood as electron (hole) tunneling through semiclassically forbidden energy gaps from one electron orbit to another in regions of momentum space where the distance between them is comparable with uncertainty of an electron impulse in the magnetic field. From the time of MB discovery [1,2] this phenomenon has started to be a tool for investigation of energy spectra and band structure details in metals and semiconductors. For example, in $Bi_{1-x}Sb_x$ monocrystals the formation under uniaxial stress of a two-bell shaped Fermi surface (FS) accompanied by intraband MB reveals the presence of a saddle point in the energy spectrum of $Bi_{1-x}Sb_x$ alloys with $x \geq 0.2$ [3]. In the present work we have observed MB in two-dimensional (2D) hole gas at *p*-GaAs/$Al_{0.5}Ga_{0.5}As$ heterointerface under uniaxial compression. The development of MB confirms the specific character of the 2D hole Fermi surface transformation under compression predicted previously by numerical calculations [4] for the heterostructures of the same layer profile configuration and carrier density, which characterize the samples in the present experiment.

2. Samples

The single heterostructure p-GaAs/$Al_{0.5}Ga_{0.5}As$ was grown in Copenhagen University by the MBE technique on a [001] semiinsulating GaAs substrate with the following sequence of layers: 0.7 μm GaAs buffer, 48 nm undoped $Al_{0.5}Ga_{0.5}As$ spacer, 7 nm of $Al_{0.5}Ga_{0.5}As$ active layer doped with Be to $5\cdot10^{23}$ m^{-3}, and finally 10 nm of Be doped up to $1\cdot10^{24}$ m^{-3} GaAs cap layer. Samples of size 0.5×0.8×3.0 mm^3, with their long axis parallel to the [110] direction, were cleaved from the structure along natural cleavage planes. The Hall bar mesa along [$1\bar{1}0$] was wet etched in the central part of the sample, and after this procedure Zn/Au contact pads were evaporated and alloyed. The contacts revealed ohmic behavior for current J up to 50 μA, while the measurements were performed with $J \leq 1$ μA. In dark at the temperature T = 1.5 K the 2D hole density $p = 7.6\cdot10^{15}$ m^{-2} and 2D hole mobility μ = 4.5 m^2/(V·s). Shubnikov-de Haas (SdH) oscillations and Hall effect were investigated at T = 1.5 K under uniaxial compression in [110] direction up to 4.7 kbar. Uniaxial stress technique is described in [5].

3. Fermi surface transformation

According to calculations of the energy spectrum in p-GaAs/$Al_{0.5}Ga_{0.5}As$ heterostructures [4], only the ground heavy hole state HH1 is populated in the samples with the mentioned above carrier density. Due to the lack of inversion symmetry in a triangular quantum well (QW) at a single heterointerface, this state is splitted on two spin nondegenerated subbands. The dispersion law in the subbands is nonparabolic. Spin splitting at the Fermi level is small and reaches ε_g = 2.14 meV in [110] direction and ε_g = 1.65 meV in [100] direction. Uniaxial compression reduces spin splitting [4] and leads to a strong qualitative transformation of the FS in both subbands (Fig.1). Contours of 2D FS in subband "0" with higher effective mass m^*_0 as well as in lighter subband "1" (corresponding FS sections S_0 and S_1) transform in a wave-vector space into elongated "ellipses". At some critical pressure P_C = 2.5 kbar the ellipses "touch" each other in [110] direction and the energy gap between spin subbands "0" and "1" in this direction $\varepsilon_0 = 0$. It remains to be very small even at pressures up to 5 kbar.

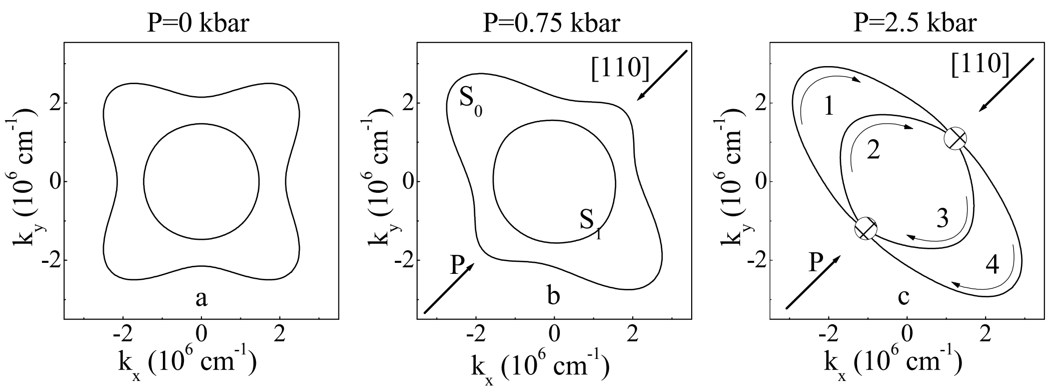

Fig. 1 FS contours S_0 and S_1 in two spin-splitted subbands of 2D heavy holes at different values of uniaxial compression along [110] direction. MB regions are shaded (c). Numbers 1, 2, 3, 4 correspond to different parts of 2D hole orbits.

4. Experimental results.

Shubnikov – de Haas fundamental frequencies F_0 and F_1 are proportional to the FS sections S_0 and S_1, and corresponding 2D hole concentration in the subbands $n_0 = eF_0/hc$ and $n_1 = eF_1/hc$. Experimental dependences of the 2D hole concentration on uniaxial compression (total and in both subbands separately) are represented in Fig.2. It should be noted, that the frequency F_1 in the "light" subband "1" may be calculated directly from SdH periods in low magnetic field (Fig. 3a), but the frequency F_0 appears only in higher filed and can be extracted from complicated SdH oscillation patterns only with the help of the Fourier transform (FT) spectra. Carrier density n_0 may be determined also as $n_0 = N_H - n_1$, where N_H – is the total carrier density determined from the Hall effect. Fig. 2 demonstrates redistribution of the carriers between spin subbands while the total carrier density decreases under compression. SdH oscillations show rather simple character at $P = 0$ but start to be much more complicated under compression (Fig.3).

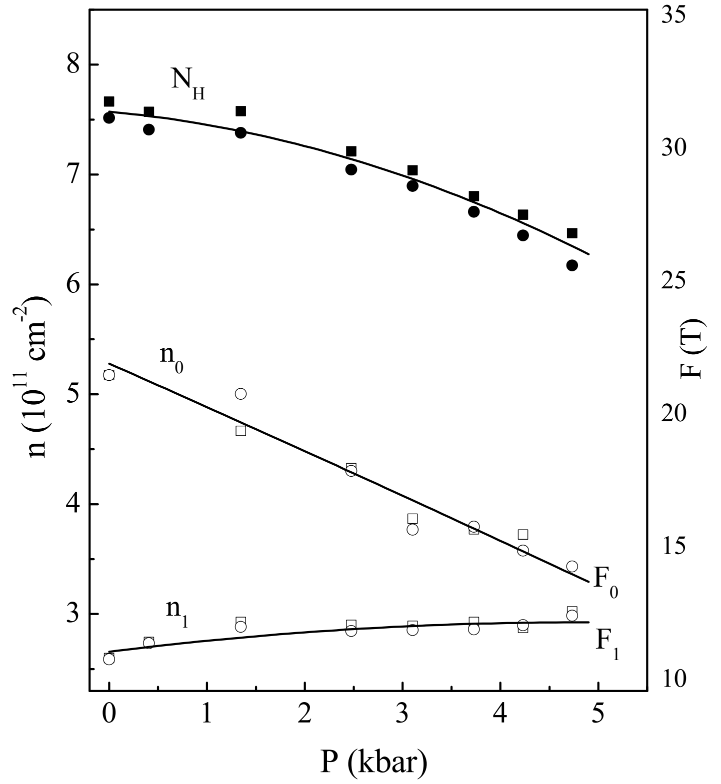

Fig. 2 Carrier density n_0, n_1 and SdH frequencies F_0, F_1 in subbands as a function of compression. N_H – total carrier concentration from the Hall effect.

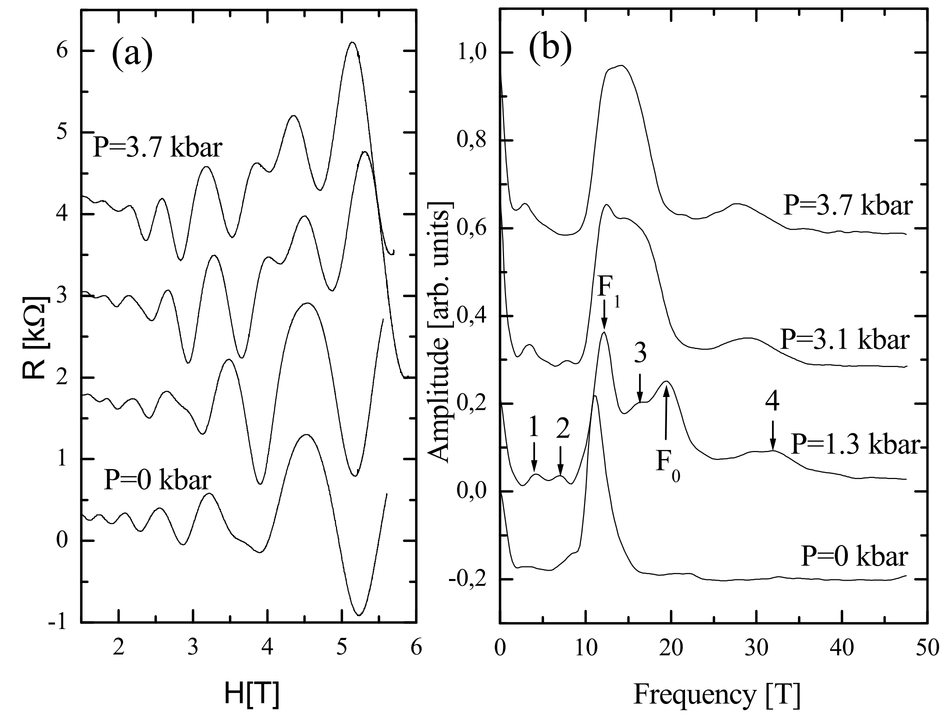

Fig.3 SdH oscillations (a) and corresponding FT spectra (b) at different values of uniaxial compression. Frequencies at P = 1.3 kbar: 1 – 4.2 T, 2 – 7.0 T, 3 – 16.4 T and 4 – 31.8 T.

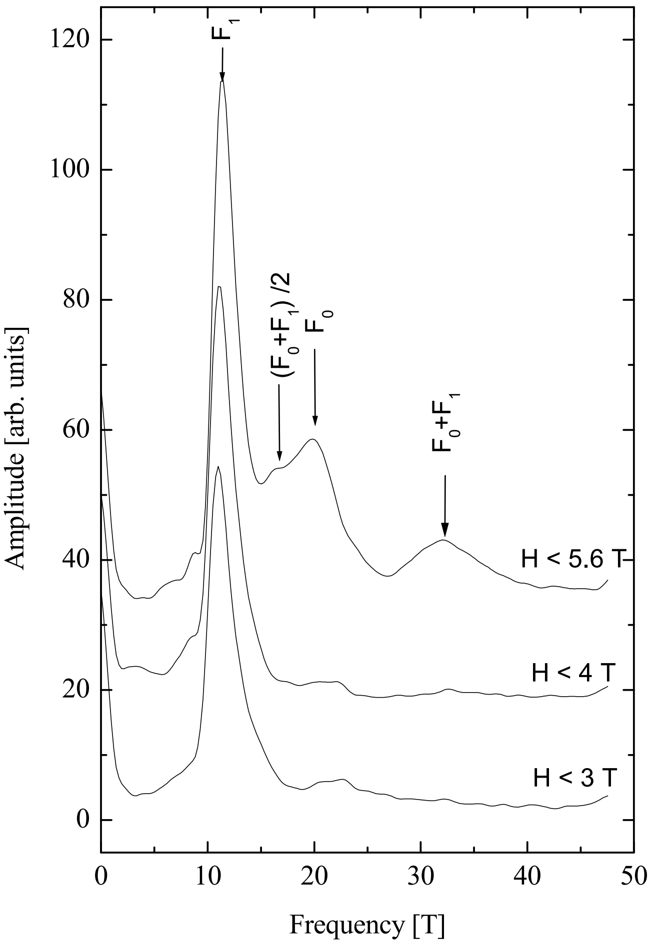

Fig.4 FT spectra in different intervals of magnetic field at zero stress.

Before we start to analyze the SdH oscillations, it should be noted that splitting of two spin subbands ε_g in the structures under investigation is very small and MB can be detected in magnetic fields up to 6T,that we have at our disposal even at zero stress. It is well known that MB probability $W = e^{H_B/H}$, where MB field $H_B = \varepsilon_g^2 / \varepsilon_F \mu$ and $\mu = e\hbar / m^* c$ [6]. According to estimations, MB with probability $W = 0.4$ may take place in magnetic fields $H \geq H_B \approx 3 \div 4$ T. FT spectra of SdH oscillations at $P = 0$ are represented for different magnetic field intervals in Fig. 4. For the interval $H \leq 4$ T only one fundamental frequency F_1 corresponding to FS area S_1 and effective mass $m_1^* = 0.2\ m_0$ can be detected in the FT spectrum, while oscillations with frequency F_0 (FS section S_0 and $m_0^* \sim 0.9 m_0$) have still too low amplitude and F_0 almost is not displayed. But at $H > 4$ T we can see in Fig.4 both fundamental frequencies F_1 and F_0 as well as the sum $F_1 + F_0$, that indicates the noticeable probability of intraband MB. For the definite interpretation of the observed MB to be a consequence of applied uniaxial stress, all FT spectra in Fig. 3b correspond to intervals of magnetic fields up to $H < 4$ T, where there is no MB at zero stress.

FT spectra start to be complicated at uniaxial compression $P \geq 1.3$ kbar (Fig. 3b). It can be explained by a corresponding transformation of 2D hole FS (Fig. 1) and growing probability of MB. In MB regime electron dynamics strongly changes because of electron possibility to leave a semiclassical orbit and move along new, previously forbidden trajectories. In the case of FS in Fig 1c where the arrows indicate the direction of the cyclotron motion we can see, that in addition to semiclassical orbits consisting from trajectories 1 – 4 (section S_0, fundamental frequency F_0) and 2 – 3 (section S_1, fundamental frequency F_1), new orbits 1 – 3 and 2 – 4 arise (frequency $(F_0 + F_1) / 2$ and its harmonic $F_0 + F_1$ in Fig. 3b).

Difference frequencies $(F_0 - F_1) / 2$ in Fig. 3b are very interesting for MB theory. They correspond to the segment ΔS between trajectories 1 – 2 and 3 – 4 and $\Delta S = (S_0 - S_1) / 2$. But

this kind of orbits is absolutely forbidden in the semiclassical theory of MB, since an electron circling along the closed boundary of the segment *ΔS* would violate the law imposed by magnetic filed on electron cyclotron motion along the part of a perimeter. The forbidden difference frequencies were detected in different materials under MB conditions: for example, in three-dimensional Mg [2] as well as in 2D organic conductors [7]. The oscillations with such frequency are supposed to originate from the *1/H*–periodic modulation of the backscattering probability due to quantum–mechanical interference between two open trajectories with common start and end points as illustrated in Fig. 1c (trajectories 1 – 2 or 3 - 4) [8]. They are not determined by oscillations of carrier density of states but arise as a result of quantum interference in a coherent MB phenomenon.
It should be noted that, according to the data in Fig. 2 the fundamental frequencies F_0 and F_1 draw each other under uniaxial compression, and under high pressure their difference cannot be detected by FT spectra in Fig. 3. This is the reason, why at higher pressure the FT spectra start to be simpler.

5. Summary

In 2D hole gas in asymmetric triangular quantum well at *p*-GaAs/$Al_xGa_{1-x}As$ heterointerface a development of magnetic breakdown between two 2D FS from different spin-splitted subbands of the ground heavy hole state has been detected under uniaxial compression. Magnetic breakdown reveals in complication of FT spectra of Shubnikov-de Haas oscillations if uniaxial compression is applied. In addition to the fundamental frequencies F_0 and F_1 corresponding to the Fermi surface sections S_0 and S_1 in the two spin–splitted subbands, the combination frequencies such as (F_0+F_1); $(F_0 + F_1) / 2$; $(F_0 - F_1) / 2$ appear. The observed phenomenon confirms the character of 2D hole FS transformation under uniaxial stress, obtained from numerical calculations. According to calculations, the subband splitting in direction of uniaxial compression decreases to zero at $P = 2.5$ kbar and this is the reason of MB development.

6. Acknowledgements

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