Suppression of hole-hole scattering in GaAs/Al$_{0.5}$Ga$_{0.5}$As heterostructures under uniaxial compression

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Resistance, magnetoresistance and their temperature dependencies have been investigated in the 2D hole gas at a [001] p-GaAs/Al$_{0.5}$Ga$_{0.5}$As heterointerface under [110] uniaxial compression. Analysis performed in the frame of hole-hole scattering between carriers in the two spin splitted subbands of the ground heavy hole state indicates, that h-h scattering is strongly suppressed by uniaxial compression. The decay time $\tau_{01}$ of the relative momentum reveals 4.5 times increase at a uniaxial compression of 1.3 kbar.

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I. INTRODUCTION

In the middle of the eighties, when a successful growth of perfect modulation doped p-GaAs/AlGaAs heterostructures initiated an intensive study of 2D hole systems, a strong positive magnetoresistance of 2D holes confined in an asymmetric triangular quantum well (QW) was observed in the region of low magnetic fields. The lack of inversion symmetry in a QW of this kind causes lifting of the spin degeneracy of the hole states at $k \neq 0$, i.e. splitting into two non spin degenerated subbands with different effective masses, sticking each other at $k=0$. In this connection the effect of positive magnetoresistance seemed to be associated with two-band carrier conductivity, although its strong temperature dependence remained to be a puzzle. Recently it was found that this puzzle can be successfully removed for p-GaAs/AlGaAs heterostructures by using the model of temperature dependent mutual scattering of the holes (h-h scattering) in the two non spin degenerate subbands.

In the present paper we show that this h-h scattering mechanism is strongly suppressed by uniaxial compression. We report on the resistance, magnetoresistance and their temperature dependencies in the 2D hole gas at a p-GaAs/Al$_{0.5}$Ga$_{0.5}$As heterointerface in the low and intermediate magnetic field range under uniaxial compression. Shubnikov-de Haas (SdH) oscillations and Hall effect were also studied in magnetic fields up to 3.5T in order to determine the carrier concentrations. We analyze these data in the frame of a two-band model with h-h scattering as it was done in Ref.

II. EXPERIMENTAL RESULTS

The samples are processed in the same way and from the same wafer as the ones reported on in Refs., where the emphasis was put on the range of high magnetic fields, and where uniaxial pressure dependence of the effective mass $m_1$ as well as the carrier concentrations $n_0$ and $n_1$ in the two subbands "0" and "1" were obtained from SdH and quantum Hall effects. The wafer is a modulation doped GaAs/Al$_{0.5}$Ga$_{0.5}$As heterostructure grown by molecular-beam epitaxy on a [001] semi-isolating GaAs substrate, and doped with Be in part of the Al$_{0.5}$Ga$_{0.5}$As. The uniaxial compression is applied along the [110] direction of a Hall bar mesa, cf. Ref. for the experimental details.

The total carrier concentration $N$ is determined by classical Hall effect ($\rho_{xy} = \frac{e}{2nN}$) in magnetic fields up to 3.5 T, while the hole concentration $n_1$ in the more light and less populated spin subband "1" is determined by SdH oscillations. The concentration in subband "0" is obtained as $n_0 = N-n_1$. The pressure dependent values of $N$, $n_0$, and $n_1$ correspond well to the data from and are used as input parameters in calculations of the 2D holes mobilities and of the mutual scattering characteristics. Galvanomagnetic characteristics, taken in low and intermediate magnetic fields $\mu B \leq 10$ and in the temperature interval 1.7-4.2K, are represented on Figs.1, 2 and show the following features:
1. At P=0 the R(B) dependence demonstrates a well pronounced positive magnetoresistance, that tends to saturation in the region μB≃5. The positive magnetoresistance strongly decreases with uniaxial compression and almost disappears at p=2.0 kbar (Fig.1a). At P>1.3 kbar, where positive magnetoresistance drastically drops, a negative magnetoresistance becomes well noticeable in intermediate magnetic fields at B>0.5 T (Fig.1a).

2. In the pressure interval where the positive magnetoresistance is still well pronounced, it reveals a strong temperature dependence, that practically disappears in the saturation region (Fig.2).

3. The resistance in zero magnetic field noticeably depends on temperature, even at T<4.2K. Under compression this dependence strongly decreases (Fig. 1 b).

4. In accordance with the previous results, the electrical resistivity R of the 2D hole gas in zero magnetic field reveals more than 2 times decrease at a uniaxial compression of P=2.6 kbar, while the total carrier concentration exhibits about 10% decrease on the background of the carriers redistribution between the two spin subbands (Figs. 3a, 3b).

III. APPLICATION OF HOLE-HOLE SCATTERING MODEL

The contribution of carrier-carrier scattering to electrical resistance is possible when two types of carriers with different mobilities make up the electric current. In an electric field the carriers will acquire different velocities, and the velocity difference can be degraded by carrier-carrier scattering, which may be described in terms of mutual friction. By writing the electric current as a sum of two terms: one proportional to the total momentum and the other proportional to the relative momentum, Kukkonen and Maldague demonstrated how the conservation of momentum (the total momentum) goes along with the mentioned contribution to the electrical resistance. In the Drude model we then have two coupled vector equations:

\[ \frac{m_0 V_0}{\tau_0} = eE + eV_0 \times B - \eta n_1 (V_0 - V_1) \]  
\[ \frac{m_1 V_1}{\tau_1} = eE + eV_1 \times B - \eta n_0 (V_1 - V_0) \]

where the subscripts "0" and "1" characterize each of the two types of carriers. Comparing these equations to the corresponding equations in Kukkonen and Maldague, it is found that the "friction coefficient \( \eta \)" is expressed as:

\[ \eta = \frac{m_0 m_1}{(n_0 m_0 + n_1 m_1) \tau_0} \]

where \( \tau_0 \) is the decay time for the relative momentum.

Solving Eqs. (1) and (2) for the velocity components and using the expression for the current density \( j = n_0 eV_0 + n_1 eV_1 = \sigma E \) we find the components \( \sigma_{xx} \) and \( \sigma_{xy} \) of the conductivity tensor to be given by the same expressions that were found in Ref. [3]:

\[ \sigma_{xx} = \frac{m_0}{\tau_0} \left[ N (Be)^2 + 2 \eta n_0 \omega_1 + \omega_0 \right] \left[ (Be)^2 + (\eta N \omega + \omega_0 \omega_1)^2 \right] \]
\[ \sigma_{xy} = \frac{m_1}{\tau_1} \left[ N (Be)^2 + 2 \eta n_1 \omega_1 + \omega_0 \right] \left[ (Be)^2 + (\eta N \omega + \omega_0 \omega_1)^2 \right] \]

where \( \omega_i = \frac{m_i}{\tau_i} \) and \( \omega = \frac{n_0 \omega_0 + n_1 \omega_1}{N} \)

Finally, the diagonal resistivity element is calculated from

\[ \rho_{xx} = \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2} \]

We have already described the way in which the total carrier concentration \( N \) and the concentrations \( n_0 \) and \( n_1 \) in the two subbands were determined from Hall effect and SdH measurements. The remaining parameters of the model were evaluated from the expressions for the high-field saturation value of \( \rho_{xx} \) :
\[ \rho_{xx} = \frac{\omega}{Ne^2} \text{ for } \mu B >> 1 \]  

and the zero-field value:

\[ \rho_{xx} = \frac{\eta(T)N\omega + \omega_0\omega_1}{(\eta(T)N^2 + n_0\omega_1 + n_1\omega_0) e^2} \text{ for } B = 0 \]

For the high-field saturation value we neglected the slight temperature dependence, cf. Fig.2, and calculated \( \omega \) from Eq.(8). Afterwards we calculated \( \eta \) from Eq.(9) at each of the experimental temperatures for an array of \( \omega_1 \)-values (\( \omega_0 \) was eliminated using Eq.(6)). Each \( \omega_1 \)-value thus gave the friction coefficient as function of temperature. We finally determined the best value of \( \omega_1 \) as the one which gave the best fit of \( \eta \) to the relation

\[ \eta(T) = \alpha T^2 \]

which is the expected temperature dependence when Fermi-Dirac statistics is prevailing; i.e. when \( kT << E_F \). In the samples under investigation \( E_F \simeq 6 \text{meV} \). The resulting parameter values \( \omega_0 \), \( \omega_1 \) and \( \alpha \) are displayed in Figs.3c and d. In Fig.3c we have replaced \( \omega_0 \) and \( \omega_1 \) by the corresponding mobilities.

### IV. RESULTS AND DISCUSSION

The behavior of the magnetoresistance at different pressures and temperatures has been calculated from expressions (4),(5) and (7) with the obtained parameter values \( \omega_0 \), \( \omega_1 \) and \( \alpha \). It is depicted on Figs.1 and 2 by dotted curves. The maximal deviation of calculations from the experimental curves does not exceed 10% for \( \Delta R = R(B) - R(0) \) in the whole interval of magnetic fields, pressures and temperatures under investigation. Thus we can conclude, that the experimental temperature dependence of the magnetoresistance at different uniaxial pressures can be well described by mutual scattering of holes in the two spin-subbands. The temperature dependence of the resistivity in zero magnetic field does not follow the h-h scattering model calculations (dotted curves) at \( T > 5 \text{K} \) (see insert on Fig.1b). It means that at higher temperature this model is not suitable because of growing \( kT \) and scattering on acoustic phonons. It should be noted that the calculations were performed only for the pressure interval up to 1.3 kbar, because the noticeable negative magnetoresistance (Fig.1), which origin is not clear at present, introduces an apparent deviation from the two-band model, described by expressions (4),(5) and (7). The pressure dependence of the mobilities \( \mu_0 \) and \( \mu_1 \) (\( \mu_i = e \omega_i \)) in the two spin subbands reveals their increase under uniaxial compression (Fig.3c), while the value of \( \alpha \), that describes the mutual friction coefficient \( \eta = \alpha T^2 \), strongly decreases (Figs.3d). The decay time \( \tau_{01} \) of the relative momentum at different magnitudes of uniaxial compression may be estimated with the help of Eq. (3), using the experimental values for \( m_1 \) and parabolic approximation for \( m_0 \) from Ref.6. The values of \( \tau_{01} \), that characterize the mutual scattering of holes in the two spin subbands, as well as the relaxation times \( \tau_0 \) and \( \tau_1 \) are represented in Table I for \( T = 4.2 \text{K} \). At zero pressure \( \tau_0 \), \( \tau_1 \) and \( \tau_{01} \) are of the same order of magnitude, but under uniaxial compression \( \tau_{01} \) reveals a much more fast increase, indicating strong suppression of the h-h scattering.

| Stress, kbar | \( \tau_0, \text{ps} \) | \( \tau_1, \text{ps} \) | \( \tau_{01}, \text{ps} \) |
|--------------|----------------|----------------|----------------|
| 0            | 5              | 7              | 11             |
| 0.65         | 6              | 9              | 18             |
| 1.0          | 8              | 10             | 30             |
| 1.3          | 11             | 11             | 47             |

TABLE I. Spin subband relaxation times \( \tau_0 \), \( \tau_1 \) and relative momentum decay time \( \tau_{01} \) at \( T = 4.2 \text{K} \) for different magnitudes of uniaxial stress.
We estimated also the decay time $\tau_{01}$ for a 2D-hole system with parameters $n_0$, $n_1$, $\omega_0$, $\omega_1$ and $\alpha$ from Ref.\textsuperscript{4} using the values of effective masses $m_0$, $m_1$ from Ref.\textsuperscript{9}, where the total carrier concentration of 2D-holes at similar GaAs/AlGaAs heterointerface is close to the one from Ref.\textsuperscript{4}. In this case the magnitude $\tau_{01}=2\text{ps}$ at $T=4.2\text{K}$ is about 6 times less than our value from Table I. This difference is most probably connected with 2÷3 times less total concentration (and Fermi energy correspondingly) of 2D-holes in Ref.\textsuperscript{4} than we have in our heterostructures.

The present experimental results are in accordance with the previous conclusion, namely that the splitting of the two heavy hole spin subbands decreases under uniaxial compression\textsuperscript{5,6}. Thus, the decrease of the positive magnetoresistance under uniaxial compression indicates a decrease of the difference between carrier properties in the two spin subbands. The hole-hole scattering, that determines the temperature dependence of the magnetoresistance at different magnitudes of uniaxial compression, does not reflect subband splitting directly. However, it is known that h-h (e-e) scattering in one-type carrier systems does not contribute to resistivity\textsuperscript{8}. In accordance with this, in rectangular QW's, where subband splitting is not expected, positive magnetoresistance is almost negligible\textsuperscript{1}.

A further result of the analysis is connected with the increase under compression of the mobilities in the two spin subbands (Fig.3c). According to Ref.\textsuperscript{6} the effective mass $m_1$ reveals an increase under uniaxial compression of 2.2 kbar and is therefore not responsible for the increase of the mobility in this subband. We are thus led to consider the growth of the mobilities to be connected with a decrease of the scattering on remote charged impurities. Such impurities exist in the active layer of $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ according to the modulation doped MBE technique, and may be supposed to be influenced by uniaxial compression. The presence of deep states in the energy gap of $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ doped with Be has been stated in Ref.\textsuperscript{4}.

V. SUMMARY

In summary, we have observed a significant influence of uniaxial compression along [110] direction on zero field resistivity and magnetoresistance of 2D holes in an asymmetric [001] triangular QW as well as on the temperature dependencies of these quantities. The experimental results can be well described in the frame of the classical two-band model, where the two splitted subbands of the ground heavy hole state constitute the two bands of the model, and where temperature dependent mutual scattering between the holes in these bands is taken into account. The results of our calculations indicate, that the hole-hole scattering mechanism in the 2D hole system under investigation is strongly suppressed by uniaxial compression. The results are in qualitative agreement with our previous findings, that the subband splitting decreases under [110] compressive strain\textsuperscript{5,6}.

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\textsuperscript{1} J.P. Eisenstein, H.L. Stormer, V. Narajanamurti, A.C. Gossard, W.Wiegmann, Phys. Rev. Lett. 53, 2579, (1984).
\textsuperscript{2} E.E. Mendez, Surf. Sci. 170, 561 (1986).
\textsuperscript{3} U.Ekenberg and M.Altarelli, Phys. Rev.B 32, 3712 (1985).
\textsuperscript{4} S.S.Murzin, S.I.Dorozhkin, G.Landwehr, A.C.Gossard; Proceedings of 23rd ICPS, Berlin 1996, Editors M.Scheffler and R.Zimmerman (World Scientific 1996), Volume 3, p. 2187.
\textsuperscript{5} O.P.Hansen, J.S.Olsen, W.Kraak, B.Saffian, N.Ya.Minina, and A.M.Savin, Phys. Rev. B 54, 1533 (1996).
\textsuperscript{6} O.P.Hansen, W.Kraak, N.Minina, J.S.Olsen, B. Saffian and A.M.Savin Phys. Stat. Sol. (b) 198, 295 (1996).
\textsuperscript{7} C.A. Kukkonen, P.F.Maldague, Phys. Rev. Lett., 37, 782 (1976).
\textsuperscript{8} V.F. Gantmakher and Y.B. Levinson, Carrier Scattering in Metals and Semiconductors, in Modern Problems in Condensed Matter Science, vol. 19. edited by V.M.Agranovich and A.A. Maradudin. (North-Holland. 1987).
\textsuperscript{9} H.L.Stormer, Z.Schlesinger, A.Chang, D.C.Tsui, A.C.Gossard and W.Wiegmann Phys.Rev. Lett. 51, 126 (1983)
\textsuperscript{10} J.Ogawa, K.Tamamura; K.Akimoto, Y.Mori, J.Appl. Phys. 63, 2765 (1988).
\textsuperscript{11} O.P.Hansen, J.Szatkowski, E.Placzek-Popko, K.Sieranski, Cryst. Res.Technol. 31, 313 (1996).
FIG. 1. Uniaxial compression influence on a) the magnetoresistance at T=1.7K and b) the temperature dependence of the resistivity of the 2D-hole gas. Dotted curves are the results of calculations with h-h scattering mechanism taken into account.

FIG. 2. Temperature dependence of the magnetoresistance at a uniaxial compression of 0.65 kbar. The results of the theoretical calculations are represented by the dotted curves on the insert.

FIG. 3. Uniaxial compression dependence of a) total carrier concentration N and spin subband carrier concentrations n₀ and n₁, b) resistivity in zero magnetic field, c) spin subband mobilities and d) friction parameter α.