PROC. 15TH INT. CONF. PHYSICS OF SEMICONDUCTORS, KYOTO, 1980
J. PHYS. SOC. JAPAN **49** (1980) SUPPL. A p. 975–978

# VALLEY SPLITTING AND VALLEY DEGENERACY FACTORS IN N-TYPE SILICON (110) AND (111) INVERSION LAYERS

M. Roos and H. Köhler

Physikalisches Institut der Universität Würzburg,
D-8700 Würzburg, GFR

It is shown from the magneto-quantum oscillations on (110) and (111) n-type silicon inversion layers that a valley degeneracy factor of 2 does not apply. The influence of a second type of electrons is directly proved from an additional Shubnikov-de Haas oscillation.

In the last few years considerable work was dedicated to silicon (110) and (111) n-type inversion layers in order to eludicate the inconsistency about the valley degeneracy factors deduced from the experiment [1-8] and the theoretical expectation. Up to now, a valley degeneracy factor $g_v(111) = 6$ was only evaluated on samples with extremely low electron mobilities [5]. In addition, g-factors higher than 2, deduced for (110) and (111) surfaces [2], had become doubtful since it was shown for (100) samples that $g = 2$ applies [9,10] in contrast to former conclusions.

Our investigations were stimulated by various experimental facts which were not in agreement with the theoretical concept, before all, by the unexpected amplitude ratios for the supposed spin-split levels in [2] attributed to neighbouring Landau quantum numbers and by the phase anomaly of the maxima positions deduced from magneto-quantum oscillations as a function of the magnetic field for a constant electron concentration. In Fig. (1) and (2) characteristic magneto-quantum oscillations are shown as a function of the gate voltage for $B \approx 10$ T and $T = 1,5$ K which, except for $V_g^+ \approx 5$ V, are almost the same. In equivalence to that the Shubnikov-de Haas oscillations are very similar, too, owing to almost the same capacity of the devices ( $n_s \approx 1,7 \cdot 10^{11}\ V_g/(V \cdot cm^2)$; $V_{th} \approx 1,5$ V; $V_g = V_g^+ - V_{th}$). Hence valley degeneracy factors $g_v = 2$ were deduced for both cases 2,3 . The phase analysis for the extrema positions in $\rho_{xx}(B)$ is shown in Fig. (3) for a (110) sample at tilt angle $\vartheta = 0$ and two different gate voltages. First the same integers n were attributed to the maxima of a camel's back structure in

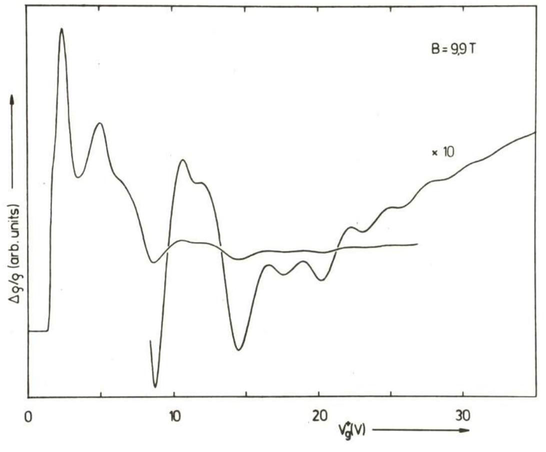


Fig. 1 $\rho_{xx}(V_g^+)$ of a (110) sample for $B = 9,9$ T and $\vartheta = 0$

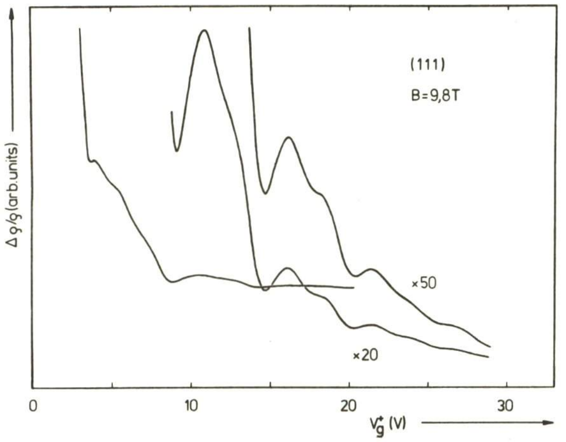


Fig. 2 $\rho_{xx}(V_g^+)$ of a (111) sample for $B = 9,8$ T and $\vartheta = 0$

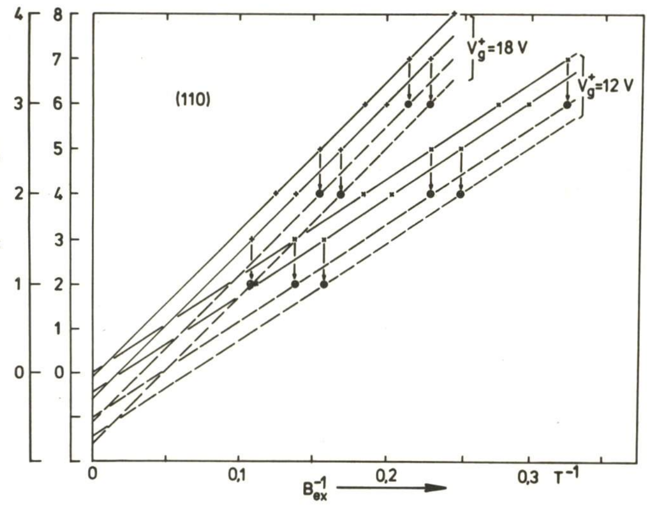


Fig. 3 Integers n attributed to the $\rho_{xx}(B)$ maxima as a function of the corresponding $B^{-1}$ values for two different gate voltages and tilt angle $\vartheta = 0$

$\rho_{xx}(B)$ and plotted as a function of the corresponding $B^{-1}$ values ( upright and tilted crosses, solid straight lines and right ordinate scale). The extrapolation towards $B^{-1} = 0$ yields almost integer and half-integer values which is not expected for a simple spin splitting, even not for $M = g \cdot m_c/(2m_o) > 0,5$. For higher gate voltages ( or higher damping ) the shift towards lower ordinate intersections is characteristic which is again in contradiction to the former interpretation [2] where $n = \pm 1/4$ should be approached for this choice of integers and $M > 0,5$ instead of $-1/4$ and $-3/4$. Almost identical results are obtained for our (111) samples. A re-arrangement of the Landau quantum numbers ( indicated by arrows ) comprehending four $\rho_{xx}$ peaks to an integer ( left ordinate scale, solid and broken straight lines ) corresponding to $g_v = 4$ yields a reduction of the relative phase deviation, however, does not allow an uncontradictory explanation except for an influence of a second type of electrons or of an additional valley splitting. This is supported by the experimental fact for (110) and (111) samples that the amplitude ratio of the camel's back structure ( e. g. in Fig.(4) for $B \approx 9$ T ) varies with increasing negative substrate bias which cannot be explained by the simple influence of only the spin splitting. Furthermore, almost the same behaviour shows up for increasing tilt angles where both peaks of the camel's back structure do not merge half-way between but the maximum with the assumed lower Landau quantum number more and more dominates while the other fades away gradually. In addition, the Shubnikov-de Haas amplitude ratio in $\rho_{xx}(B)$ clearly reveals both peaks of the camel's back structure, e. g. between 5 and 8 V in Fig.(1), not to belong to different Landau quantum numbers.

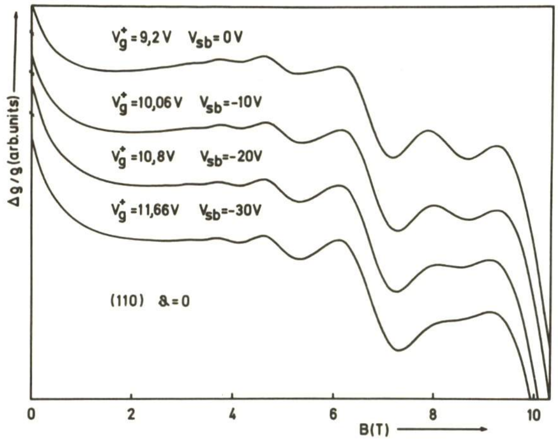


Fig. 4 Shubnikov-de Haas oscillations of a (110) sample for constant electron concentration but different values of the substrate bias $U_{sb}$ ( $\vartheta = 0$ )

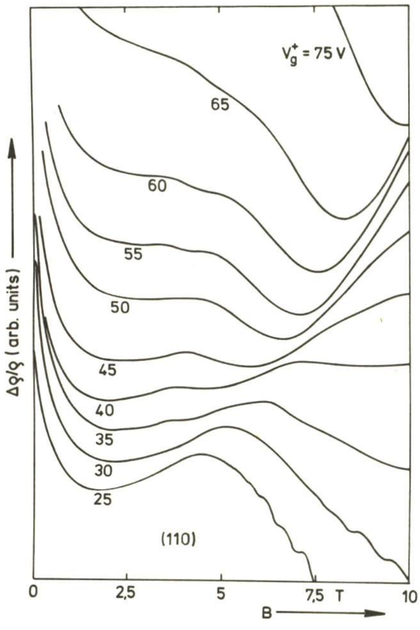


Fig. 5 "Second" $\rho_{xx}(B)$ oscillation of a (110) sample at high gate voltages for $\vartheta = 0$: The "fundamental" oscillation is still visible for $V_g^+ =$ 25 V and 30 V at high magnetic fields

The investigation of the magnetoresistance for high gate voltages yields an explanation for the negative differential background ( e. g. in Fig. (4) starting from $B \approx 5$ T ) characteristic for all our (110) and (111) samples. In Fig. (5) for increasing gate voltage an additional magneto-quantum oscillation shows up after the "fundamental" oscillation has vanished below B = 10 T ( e. g. still visible for $V_g^+ = 30$ V and $B > 7{,}5$ T ). The "second" oscillation is clearly resolved for $V_g^+ = 35$ V and has to be attributed to a second type of electrons in the surface channel since a variation of the substrate bias and hence the threshold voltage $V_{th}$ above $V_g \cdot d_{co}/d_{fo}$ does not influence the observed structure ( $d_{co}$: thickness of channel oxide; $d_{fo}$: thickness of field oxide neighbouring the channel ), thereby excluding the influence of a bypass channel. The "second" oscillation is periodic in 1/B. The position of the deepest minimum in $\rho_{xx}(B)$ of Fig. (5) is plotted in Fig. (6) as a function of the corresponding gate voltage yielding a linear relation which is extrapolated towards the threshold for the channel conductance showing that the second type of states is occupied from the beginning of lowest electron concentrations. The ratio of the Shubnikov-de Haas frequencies is about 9 with reference to the same gate voltage $(V_g^+ - V_{th})$ in average yielding about 11 % of the second type of electrons for $g_v = g_v' = 2$ but only less than 6 % for $g_v = 2g_v' = 4$. In the same way additional structures in the magnetoresistance are observed for (111) samples at high gate voltages though the resolution is poorer and does not allow a quantitative evaluation.

However, this result implies that the influence of a second type of electrons has to be expected even

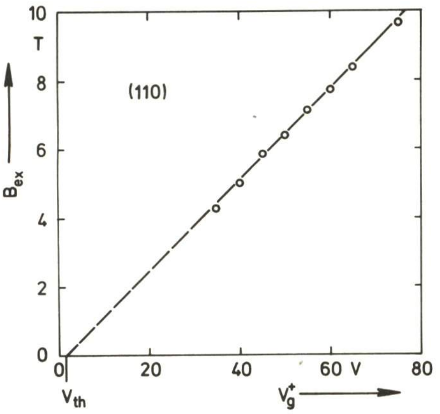


Fig. 6 Magnetic field position of the deepest minimum in $\rho_{xx}(B)$ of Fig. (5) as a function of the gate voltage

at lower gate voltages, in particular, for high magnetic fields where the Fermi energy shows a step-like variation with the gate voltage.

A possible explanation which fits to all experimental results is based on the assumption that the lowest valleys are separated into groups of two in our (110) and (111) samples which, for instance, could be the case for a small surface misorientation and possibly internal mechanical stress. Since, in addition, different mass parameters shift the electric subband edges and simultaneously the centre of charge as well as the penetration depth of the wave function into the oxide, the total energy of the capacitor is smallest for the electrons in average nearest to the gate, the states of which are occupied first. Subsequently, for (110) surfaces the rest of i = 0 valleys is filled yielding a shift of about $\hbar\omega_c/2$ with respect to the first pair of valleys. Consequently, the "second" magneto-quantum oscillation for our (110) samples should result from the influence of i = 0' electrons with $g_v' = 2$. Their effect is of essential importance also at low gate voltages where the highest steps in the Fermi energy occur between the spin-split levels of a valley pair, diving into the i = 0' level ladder which hence contributes to $\sigma_{xx}$ with its lowest states only since the i = 0' subband edge is shifted to higher energies with increasing surface electric field. The explanation of the phase anomaly for the $\rho_{xx}(B)$ extrema positions by an additional valley splitting of the valley pairs as compensation for the influence of the i = 0' electrons fails since this effect should vanish for low gate voltages which is not observed.

For (111) surfaces the same arguments apply where the degeneracy of the three valley pairs may be lifted by a slight misorientation and possibly mechanical stress, too. The influence of a second type of electrons is also shown from an additional structure in $\rho_{xx}(B)$ at high gate voltages. Hence $g_v(111) > 2$ has to be concluded. A re-examination of all data on "high" and "low" mobility samples seems necessary, in particular, since the results shown in [5-8] are nonperiodic in the gate voltage and therefore the assignment of quantum numbers and the assumption of an additional valley splitting seems doubtful.

1) A. A. Lakhani and P. J. Stiles: Phys. Lett. 51A (1975) 117.
2) T. Neugebauer et al.: Solid State Commun. 17 (1975) 295.
3) D.C. Tsui and G. Kaminsky: Solid State Commun. 20 (1976) 93.
4) G. Dorda, H. Gesch, I. Eisele: Solid State Commun. 20 (1976) 429.
5) D.C. Tsui and G. Kaminsky: Phys. Rev. Lett. 42 (1979) 595.
6) D.C. Tsui and G. Kaminsky: Yamada Conf. II El. Prop. 2D Systems, Japan 1979, p. 409.
7) G. Landwehr: ibid. [6], p. 420
8) T. Englert et al.: Solid State Commun. 33 (1980) 1167.
9) H. Köhler and M. Roos: phys. stat. sol. (b) 95 (1979) 107.
10) H. Köhler and M. Roos: phys. stat. sol. (b), to be published.