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Surface quantum oscillations in silicon (100) inversion layers under uniaxial pressure

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Surface quantum oscillations in (100) n-type silicon inversion layers were studied as a function of uniaxial compression. Due to an increase of the cyclotron mass the ratio of spin splitting to Landau splitting Δ increases continuously with pressure. At $p = 3.6$ kbar, Δ has roughly doubled. At zero pressure only the light-mass subband E_0 is occupied, whereas in the high-pressure limit only the heavy-mass subband E_0' is populated. However, a simultaneous occupation of E_0 and E_0' at medium pressures must be excluded, since the measured valley degeneracy factor is 2 in the whole pressure range investigated. An interaction between E_0 and E_0' must be invoked, which generates a new twofold degenerate electron ground state at medium pressures. The pressure value at which the interaction becomes significant and also the cyclotron mass seem to depend on the magnetic field. Qualitatively, the experimental results can be explained by a theory of Kelly and Falicov which is based on the existence of charge-density waves in the silicon surface.

I. INTRODUCTION

It has been known for several years that in silicon inversion layers the energy bands are grouped into electric subbands.[1] These arise from the boundary quantization of electrons which are confined to a narrow space-charge layer at the surface. The multivalley-conduction-band structure of silicon is also reflected in the nature of the electric subbands. The effective-mass theory predicts that the lowest subband on a (100) surface should be twofold degenerate and that another fourfold-degenerate system is raised in energy. For a (111) surface, the degeneracy should be 6, and only a single subband system should be present. On (110) surfaces, the degeneracy factor of the low-energy subbands should be 4. When these predictions were checked[2] experimentally, it turned out that for all three surface orientations the valley degeneracy factor was 2. When subsequently the angular dependence of the conductivity in (111) surfaces was investigated,[3,4] it turned out that the conductivity was isotropic. This is quite unexpected, if only two valleys located on a common axis in $\vec{k}$ space are occupied, because of the mass anisotropy of a single valley. These findings show that our present understanding of the subband structure of n-type silicon inversion layers is inadequate.

A powerful method to vary the subbands on silicon surfaces is the application of uniaxial stress. It is well known from bulk silicon[5] that the energy gap decreases with decreasing lattice constant. Consequently, application of uniaxial compression[6] in the [100] direction of bulk silicon lowers the energy of two valleys and raises the energy of the four remaining ones. This results in an electron transfer, and in connection with the anisotropy of the electron mobility for a single valley, a pronounced piezoresistance effect arises. Application of this mechanism to inversion layers leads to a splitting of the fourfold-degenerate subband system E_0' into two twofold-degenerate bands $E_0'^{+}$ and $E_0'^{-}$ and to a shift of these levels. Whereas the lowest twofold-degenerate subband raises in energy with uniaxial compression in the [100] direction, the subband $E_0'^{-}$ is lowered so that the energy difference $E_0'^{-} - E_0$ is reduced. By applying uniaxial compression of about 3 kbar, Eisele *et al.*[7] succeeded in a complete repopulation of the two subbands. The data were obtained by studying Shubnikov–de Haas (SdH) oscillations. A puzzling result was that the period of the quantum oscillations did not change with compression, which would be expected as a consequence of the change of the relative Fermi energy with pressure. Puzzling results were also obtained when cyclotron resonance was investigated under uniaxial pressure.[8] At $P = 1.5$ kbar, a sufficient number of electrons should be transferred to the heavy-mass subband so that a second cyclotron resonance line should be observed. Instead, only a single line was seen with an apparent strong pressure dependence of the cyclotron mass at low carrier concentrations. Another unexpected result was a substantial increase of cyclotron mass with increasing temperature.[9] In this case, no second cyclotron line arising from the thermal population of the higher subband was found.

The anomalous degeneracy factors for the [111] and [110] orientations in conjunction with the experimentally observed increased mass[2] motivated

Kelly and Falicov[10,11] to study the problem theoretically. They performed a self-consistent many-body calculation of electric subbands for n-type silicon inversion layers and suggested the existence of charge-density waves on (111) and (110) surfaces. Although the paramagnetic state should be stable in unstressed (100) surfaces, the application of uniaxial pressure brings the subbands E_0' and E_0 closer together and makes charge-density waves feasible. These arise according to Kelly and Falicov by an exchange interaction between electrons in different valleys. Because for a (111) surface, the order parameter is equal for the three main directions, domains should exist. If these are randomly distributed, the transport properties are expected to be isotropic. The application of uniaxial stress should, however, favor domains of a particular orientation.

The evidence for the existence of charge-density waves is, however, incomplete. It is not clear whether the electron-phonon coupling between different valleys is strong enough that charge-density waves can exist at silicon surfaces. It was thought desirable therefore to obtain more experimental information. The work presented in this paper is an extension of previous pressure experiments on metal-oxide-semiconductor field-effect transistors (MOSFETs).[7,12,13] It is well known that the determination of effective masses from SdH oscillations in a simple way is only possible if the harmonic content of the oscillations is negligible. One of the causes of harmonic content is spin splitting. In a quasi-two-dimensional system one has, however, the possibility to vary the Landau splitting by tilting the samples in a magnetic field. The ratio of Landau splitting to spin splitting (the latter depends only on the magnetic field as a whole) may be adjusted in such a way that the energy levels in a magnetic field are equidistant. In such a case, SdH oscillations may be analyzed up to rather high carrier concentrations. It has been shown[2] that the effective mass is independent of the tilt angle. The same holds for the g factor.[23] Moreover, we recorded SdH oscillations at a constant magnetic field as a function of the gate voltage at various pressures.

II. EXPERIMENTAL ARRANGEMENT

The n-channel silicon MOSFETs which were 400 μm long and 40 μm wide had a gate oxide of 120-nm thickness. Uniaxial compression or dilation were produced by bending a silicon slab about 20 mm long and 0.2 mm thick on the top of which MOSFETs were located. Because the uniaxial strain has its maximum close to the clamping of the samples, the device closest to this point usually was used. We generated uniaxial stress in the surface up to 3.6 kbar. The direction of current and pressure in our (100) devices was always [001]. The sample holder could be rotated with respect to the magnetic field, which was generated with a superconducting coil. In our experiments, the angle φ between surface normal and magnetic field B was 0°, 44°, 54.8°, and 61°. The orientation had a precision of about $\frac{1}{2}$° and was determined from the angular dependence of the position of the SdH minima, which follows a cosine law.

III. RESULTS

A. Experiments with a magnetic field perpendicular to the surface

In Fig. 1, recordings of the channel resistance as a function of the gate voltage at a magnetic field of 8.6 T are shown for various pressures up to 3.31 kbar. The data at the top of the figure were obtained at zero pressure, and the recording at maximum compressive stress is plotted at the bottom. Hardly any changes were visible for tensile stress. SdH oscillations at constant magnetic field occur when the Fermi level (which is increasing with increasing gate voltage) passes through Landau levels.[1] This method has the advantage that changes in the oscillatory pattern can be visualized simultaneously for various surface-carrier concentrations. For $P=O$, the usual form of the oscillations was obtained. At small quantum numbers, both Landau and spin splitting are observed. For the quantum number $n=1$, the valley splitting is resolved. This effect will, however, not be discussed subsequently, because it does not change with pressure within the experimental accuracy.

Application of pressure initially causes a decrease of the amplitude of the oscillations with increasing pressure and, at higher pressure an increase. If a particular minimum in the $P=0$ curve, e.g., that between $n=1$ and $n=2$ (broken line to the left) is considered, one finds that it decreases slowly with increasing uniaxial compression, disappears and then reappears as a maximum at the same position on the V_g scale. This is equivalent to a 180° phase shift between the upper and the lowest recording. Since no change in the threshold voltage V_{th} was observed, a variation in V_{th} cannot be the origin of the shift. In Fig. 2, the quantum numbers have been plotted against the positions of the minima on the gate voltage scale with the pressure as parameter. (In order to show the data in a single figure, integers have been added to the actual quantum numbers for the pressure

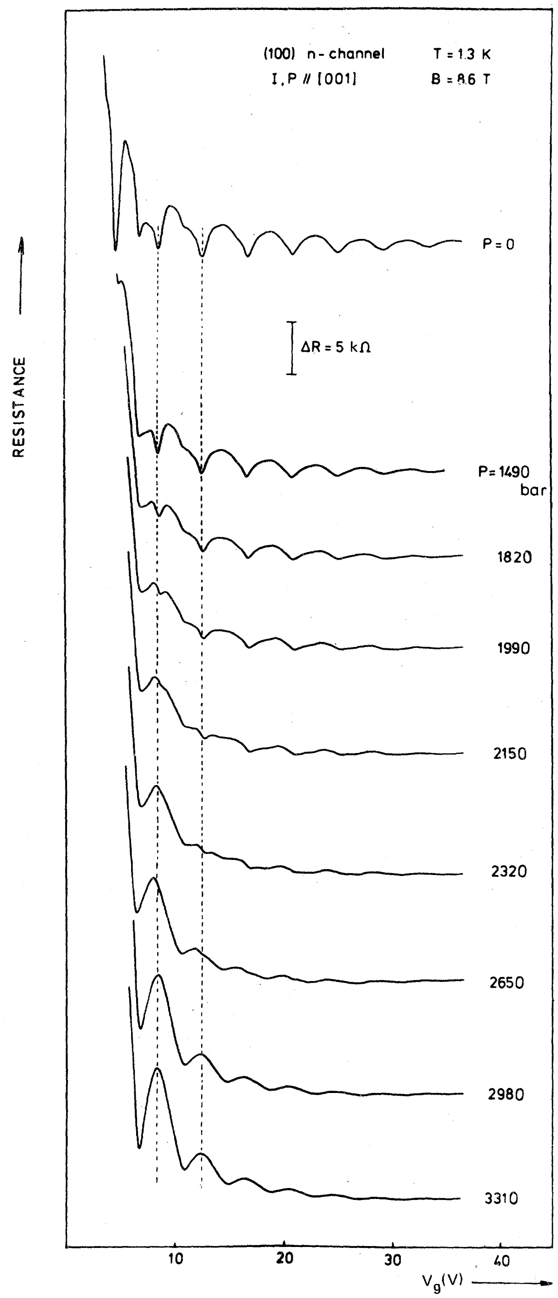

FIG. 1. Channel resistance of a (100) silicon inversion layer at a transverse magnetic field of 8.6 T as a function of the gate voltage V_g with the uniaxial pressure P as parameter.

results.) The 180° phase change can be seen up to quantum number $n=6$, but clearly, the effect of pressure is most pronounced at small quantum numbers. For $P=1.7$ and 2.04 kbar, the slope has decreased for $n=6$. Formally, this could be interpreted as a change in period. We believe, however, that we are dealing with an artifact

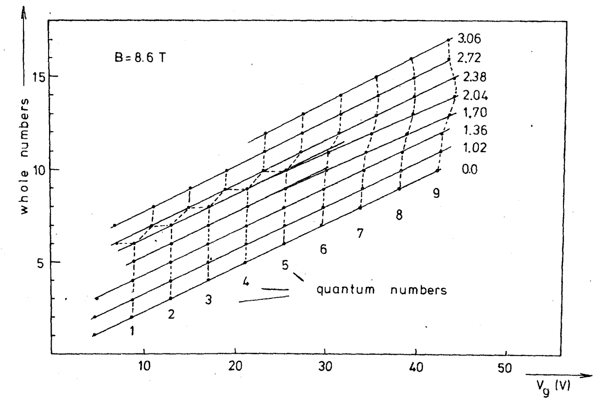

FIG. 2. Positions of minima on the gate voltage scale versus whole numbers with the pressure as parameter.

without physical significance for our present problem, because no break is visible at higher pressures.

If the relative amplitude of the oscillations $|\Delta R/R_0|$ is plotted for different quantum numbers as a function of pressure, one obtains curves with a pronounced minimum (Fig. 3). The minimum shifts with increasing carrier concentration to higher pressure values. For quantum numbers $n=7$ and $n=8$, only a monotonic decrease of the amplitude is observed.

The phase shift of 180° can be explained by a change in the ratio of spin splitting to Landau splitting. Although a change in effective mass m^* leaves the period of the oscillations unchanged, it influences the ratio of spin splitting to Landau splitting[1] because the Landau splitting depends on m^*, but the spin splitting does not. For very sharp Landau levels, this would be irrelevant for the shape of the quantum oscillations because of the jumping of the Fermi level with increasing gate voltage.[1] In reality, the density of states is considerably broadened which results in a broadening of the oscillations. Two adjacent energy levels can only be separated if their energy difference is larger than the half-width of the peaks. The most pronounced minima can be observed between the levels for which the energy difference is the largest. For n-type inversion layers of (100) orientation under zero stress, this is the case for energy levels which differ by one in their Landau quantum number, because the spin splitting is smaller than half of the Landau splitting. This can be characterized by the conditions $gm^*/2m_0 < \frac{1}{2}$; when g is the Landé g factor. The spin splitting may be observed as additional structure in this case. An increase of the effective mass by a factor of 2 leads to a reduction of the Landau splitting to half the original value, in this case

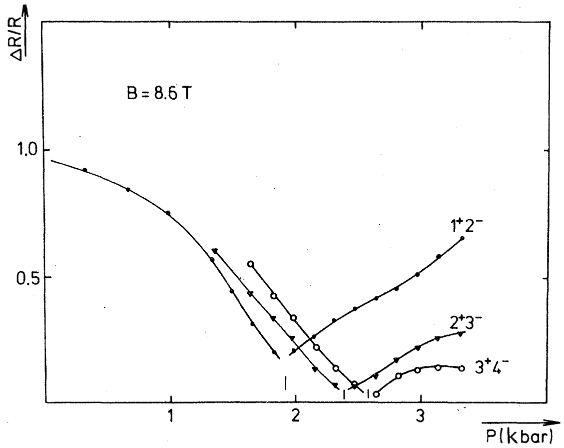

FIG. 3. Relative amplitude of particular oscillations in the channel resistance as a function of pressure. The electron concentrations corresponding to the labeling 1^+2^-, 2^+3^-, and 3^+4^- are 1.2×10^{12} cm^{-2}, 2×10^{12} cm^{-2}, and 2.8×10^{12} cm^{-2}, respectively.

$gm^*/2m_0$ will be larger than $\frac{1}{2}$. Now, the largest energy difference occurs between different spin levels, and the pronounced minima in the oscillatory magnetoresistance are caused by the spin splitting. It can occur that for strong line broadening the spin levels belonging to adjacent quantum numbers overlap so much that the Landau splitting can no longer be resolved. This will result in a phase shift of 180°, as we have observed by applying uniaxial compression of 3.3 kbar. Our data can be explained by the assumption that at high pressure the higher subband system is occupied with electrons of an effective mass roughly twice as the mass in the lower subband system. A sudden increase of the mass to about $0.45m_0$ at high uniaxial compression has been observed recently[7] for carrier concentrations up to $8\times10^{11}/cm^{-2}$. Our results agree with these findings. In addition, we can state that the 180° phase change under pressure (and, consequently, the population of the heavy-mass subband) not only occurs at small gate voltages, but up to surface-carrier concentrations of about $4.4\times10^{12}/cm^{-2}$. This result is significant insofar that the data were obtained beyond the activated range where the transport properties of silicon inversion layers are still incompletely understood.[14]

Another interesting result of our experiments is that the period of the oscillations (the distance of the minima on the V_g scale) does not change and that the valley degeneracy factor under uniaxial pressure is always 2. The structure which can be seen in Fig. 1 at pressures of 2.15 and 2.32 kbar between gate voltages of 12 and 25 V can be attributed to spin splitting and not to a second period. A valley degeneracy factor of 4 would lead to a larger period, not to a smaller one.

B. Experiments with tilted samples

In quasi-two-dimensional systems, a change of the ratio of spin splitting to Landau splitting cannot only originate from a change in effective mass, but also from a tilting of the sample in the magnetic field B. This method was at first employed to determine the electronic g factor in silicon inversion layers.[15] Whereas the Landau splitting depends only on the component of the magnetic field perpendicular to the surface, the spin splitting depends on the magnetic field as a whole. The ratio of spin splitting to Landau splitting is characterized by the expression $gm^*/2m_0\cos\varphi$, where φ is the angel between B and the surface normal. It is obvious that doubling of the effective mass and tilting the sample by 60° result in the same energy level scheme.

It is well known[1] that the effective mass can only be derived in a simple way from the temperature dependence of the oscillations if the oscillations in $1/B$ are sinusoidal (B is the magnetic induction). This is the case at large quantum numbers if spin splitting is absent, because then the harmonic content is negligible. The harmonic content can be reduced, however, by tilting the sample with respect to the magnetic field in such a way that the spin splitting is a multiple of the Landau splitting. In this case, sinusoidal oscillations can be obtained for not too small quantum numbers. The coincidence of two adjacent Landau levels can be experimentally checked by looking for a maximum in the amplitude of the quantum oscillations as a function of the tilt angle.

In the following, we have studied whether the application of uniaxial pressure can lead to a coincidence of adjacent spin-split Landau levels. For a mass of $0.43m_0$, a pressure of 3.3 kbar and a tilt angle $\varphi = 0°$, $gm^*/2m_0$ is roughly 0.7. In order to obtain coincidence, it is necessary to tilt the sample. A tile angle of 60° would lead to a ratio of spin splitting to Landau splitting twice as large. This means that it should be possible to record a coincidence if the effective mass increases continuously from $0.2m_0$ to $0.43m_0$. From the coincidence, one can determine m^*, provided that the g factor does not change. Moreover, one can determine the effective mass at coincidence from the temperature dependence of the amplitude of the SdH oscillations as usual. This has the advantage that m^* can be deduced from high magnetic-field data at rather high electron concentrations.

As expected, it was possible to obtain coinci-

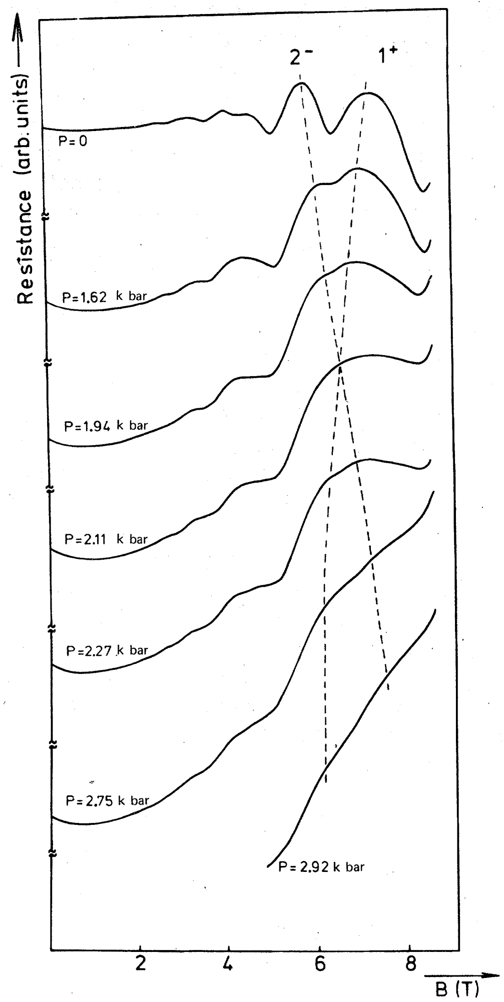

FIG. 4. Channel resistance as a function of a magnetic field for a surface electron concentration of 5.8 $\times 10^{11}$cm^{-2} with the pressure P as parameter. The magnetic field B was tilted 54.8° with respect to the surface normal.

dence between adjacent Landau levels by uniaxial compression of a sample which was tilted 54.8° with respect to the magnetic field. The data are shown in Fig. 4. The channel resistance has been plotted at constant gate voltage as a function of the magnetic field with the pressure as parameter. It can be recognized that the distance between the 2^- and 1^+ maxima decreases with increasing pressure and that a crossing occurs around 2 kbar. Although in Fig. 4 the two peaks at 2.92 and 2.75 kbar cannot be distinguished too well, an inspection of the original data leaves no doubt about the existence of two separate maxima. From the coincidence, a value of $\Delta = gm^*/2m_0 = 0.58$ is obtained. The same experiments were performed for tilt angles of 44° and 61°. Together with a

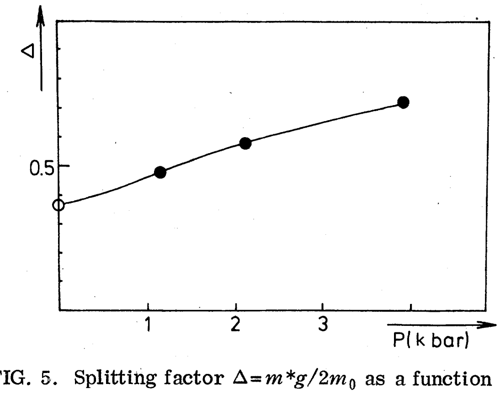

FIG. 5. Splitting factor $\Delta = m^*g/2m_0$ as a function of pressure.

value for $gm^*/2m_0$ for zero pressure, our results are plotted in Fig. 5. The number obtained for $P = 0$, which agrees with previous findings[15,18] was deduced from experiments with a different sample. It is evident that at the highest pressure applied $\Delta = gm^*/2m_0$ has roughly doubled. If the g factor for a surface-carrier concentration of 5.8×10^{11} cm^{-2} is taken into account,[1] one finds that m^* increases from $0.22m_0$ at $P = 0$ to $(0.44 \pm 0.04)m_0$ at $P = 3.7$ kbar. This strongly suggests that at the highest pressure the second subband system is populated in agreement with recent findings of Eisele *et al.*.[7] The data obtained for $P = 1.15$ and 2.1 kbar suggest that the mass increases continuously with increasing pressure. The rate of increase of m^* is compatible with that observed in a cyclotron resonance experiment under uniaxial compression.[8] It has been tacitly assumed, that the g factor for the light- and the heavy-mass subband are the same. This might not necessarily be true. If the g factor for the heavy-mass band were smaller than anticipated, the mass under high pressure would become larger. It should be noted, however, that the g factor and its dependence on the carrier concentration of electrons in silicon inversion layers of (100), (110), and (111) orientation do not differ significantly, although the cyclotron mass of electrons in (110) and (111) planes is about a factor of 2 larger than in (100) planes. These findings suggest that the assumption made about the g factor of the heavy-mass (100) subband is reasonable.

It is not only possible to determine coincidence of two adjacent Landau levels by recording the position of two particular maxima; one can also estimate the coincidence from the dependence of the amplitude of the oscillations on compression. Typical data for a tilted sample are shown in Fig. 6. Because the amplitude of the oscillations both for tilted and untilted samples depends on the

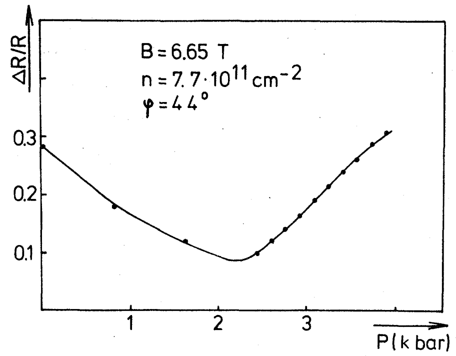

FIG. 6. Relative amplitude of a particular quantum oscillation for a surface electron concentration of 7.7 $\times 10^{11}$ cm^{-2} and a tilt angle of 44° as a function of the uniaxial pressure P.

pressure, it is necessary to unfold the data which can be done by making a few reasonable assumptions. Within the experimental accuracy, the points of coincidence agreed.

We derived, in addition, the cyclotron mass under high pressure ($P \approx 3.7$ kbar) from the temperature dependence of the amplitude of the SdH oscillations. For $\varphi = 44°$, coincidence is almost established. For the carrier concentrations $n = 7.7 \times 10^{11}$, 1.44×10^{12}, and 1.84×10^{12} cm^{-2}, the masses were determined between 2.4 K and 1.2 K. The respective values obtained were $0.55m_0$, $0.53m_0$, and $0.53m_0$. The estimated error is $\pm 0.04m_0$. Previous experience with the evaluation of masses from the SdH effect shows that this estimate is realistic. The masses are higher than those which were determined at lower carrier concentrations. In the recent data of Eisele *et al.*,[7] there is a hint, that m^* increases with increasing carrier concentration. It should be recalled that SdH masses are enhanced due to electron-electron interactions with respect to the bulk values.[16] The enhancement can exceed 10% at electron concentrations around 10^{12} cm^{-2}. We refrained from determining m^* at still higher carrier concentrations because the oscillations were no longer sinusoidal. It is obvious that this type of analysis again suggests that a transfer of electrons has occurred. We would like to emphasize that a check of the damping of the oscillations as a function of the magnetic field showed that the Dingle temperature at $P = 0$ and $P = 3.7$ kbar was the same between 1.2 and 2.4 K in the range of electron concentrations investigated. It turned out, however, that it was not possible to deduce the effective mass from the temperature dependence of the SdH oscillations at medium pressures, even if coincidence was realized. A naive analysis of the data always leads to masses between 0.22 and $0.24m_0$. A subsequent inspection of the damping of the oscillations revealed, that it could not be characterized by a temperature-independent Dingle temperature. In a few cases, it was not even possible to describe the magnetic-field dependence of the oscillations at a fixed temperature with a single damping parameter. Consequently, one should not deduce the mass in the usual fashion in the intermediate range. It seems, that for higher electron concentrations the situation is different, that in this case a Dingle temperature may be defined.[7]

In order to check whether the anomalous damping in the intermediate pressure range might be caused by a superposition of the oscillations arising from "light" and "heavy" electrons, we studied quantum oscillations as a function of the magnetic field at a tilt angle of 44° in some detail. Data are shown in Fig. 7.

The oscillations at $P = 0$ can entirely be attributed to the "light" electrons, whereas at a pressure of $P = 3.49$ kbar the influence of the "heavy" electrons prevails. At an intermediate pressure of 2.6 kbar, two periods seem to be present. At low magnetic fields, only the oscillations originating from electrons with $m = 0.22m_0$ show up, whereas

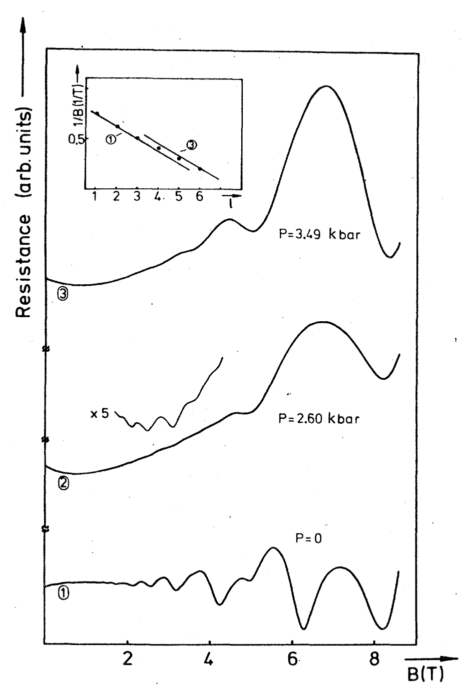

FIG. 7. Channel resistance as a function of a transverse magnetic field B at pressures 0, 2, 6, and 3.49 kbar. In the insert, the positions of the maxima have been plotted on a $1/B$ scale versus whole numbers. The angle between B and the surface normal was 44°, and the electron concentration $n = 7.7 \times 10^{11}$ cm^{-2}.

at high magnetic fields, the "heavy" electron oscillation dominates. This kind of behavior is reflected in the insert of Fig. 7, where the positions of the maxima have been plotted on a $1/B$ scale as a function of whole numbers. The two straight lines represent the data of curves 1 ($P=0$) and 3 ($P=3.48$ kbar). Both lines have the same slope, but show an offset due to the phase shift. The maxima of curve 2 which are drawn as points lie on curve 1 at small magnetic fields and on curve 3 at high B values. It should be emphasized, however, that at the intermediate pressure of 2.6 kbar the period which can be attributed to the light electron subband, has *not* changed with respect to the $P=0$ data.

C. Subband splitting as a function of pressure

In Fig. 3 the pressure dependence of the amplitude of quantum oscillations recorded at a constant magnetic field, has been plotted for different quantum numbers. A pronounced minimum in the relative change of resistance shifted with increasing carrier concentration to higher pressures. It is possible to estimate the energy difference of the two subband E_0 and E_0' from these data.

The analysis of our data suggests that at zero pressure the twofold-degenerate light electron subband is occupied whereas at the highest pressure applied, the heavy-mass subband is populated. The surprising result of the pressure experiments is that the valley degeneracy factor does not change and that the electron concentration—which can be deduced from the period of the oscillations—is constant. Hence, a simple transfer of electrons under uniaxial pressure, which occurs in bulk silicon, must be excluded. Obviously, one is confronted with a dilemma. Our results strongly indicate that at 3 kbar the E_0' subband is populated. On the other hand, we cannot observe the decrease of the electron concentration in subband E_0 with increasing pressure. In order to explain this apparent contradiction, we have to invoke an interaction between the E_0 and E_0' subbands. The interaction will increase with decreasing energy difference between the two subbands. We expect that due to the interaction no crossing point of the subbands E_0 and E_0' at a particular pressure exists, that there is always an energy gap. At intermediate pressures, one cannot distinguish between E_0 and E_0' states. A distinction is only possible at $P=0$, where the E_0 state is well defined, and at high pressure where the E_0' state is well characterized. This model allows us to avoid the difficulty with the nonobserved degeneracy factor of 4 at intermediate pressures.

A theory based on the same model has recently been proposed by Kelly and Falicov.[17] They were motivated to treat the problem by earlier findings of Dorda and coworkers.[7,12] The new theory is based on a charge-density wave ground state in analogy to the state which was proposed to explain the anomalous degeneracy factors for (111) and (110) n-type silicon inversion layers. The paramagnetic state is stable for zero pressure when the light-mass subband is occupied and again at high pressure when the heavy-mass subband is well defined. At intermediate pressures, the charge-density wave ground state becomes favorable, which is composed of combinations of the light- and heavy-mass states. No crossing of the E_0 and E_0' subbands should occur, and the valley degeneracy factor should always be 2. In the intermediate pressure range, a first- and a second-order phase transition are predicted. The pressures where the transitions occur depend on the surface-carrier concentration. One is inclined to assume that the minima in the amplitude which we have observed and which are shown in Fig. 3 are identical with the maximum energy of the coupled state. It seems reasonable to assume that the minimum in the amplitude is not far from the virtual crossing point of E_0 and E_0'. If this assumption is correct, the subband splitting at zero pressure may be estimated, making use of the known deformation potential of silicon and its elastic constants. It has been pointed out to us by Kelly and Falicov that the stress at which the charge-density wave interaction occurs is not simply related with the difference in energy between E_0 and E_0' at zero stress. Therefore, we did not elaborate on the possibility that the maximum of the interaction might depend on the position of the Fermi level. Thus, the estimate of $E_0'-E_0$ (at $P=0$) should be rather crude. We obtained the following numbers for $E_0'-E_0$: 16.4 meV for $n=1.2\times10^{12}$ cm^{-2}; 21.3 meV for $n=2\times10^{12}$ cm^{-2}; and 23.0 meV for $n=2.8\times10^{12}$ cm^{-2}. It should be pointed out that the shift in the minima of the amplitude of the quantum oscillations with increasing carrier concentrations towards higher pressures is in qualitative agreement with theory.

In our discussion, we have neglected that a high magnetic field might modify the electron energies. The zero-point energy of $\frac{1}{2}\hbar\omega$ at zero pressure, when the subband E_0 is well defined, is roughly twice as large as the zero-point energy at high pressure when the heavy-mass subband prevails. This will influence the pressure at which the interaction occurs, and it will cause a shift towards smaller energy differences $E_0'-E_0$ at $P=0$.

IV. DISCUSSION AND CONCLUDING REMARKS

When we studied the ratio of spin splitting to Landau splitting Δ as a function of uniaxial compression we found that Δ increased roughly by a factor 2 at $P=3.7$ kbar. The change in $\Delta = gm^*/2m_0$ is mainly attributed to a change in the effective mass. The theoretical justification for this is, that silicon is a wide band semiconductor with a small spin-orbit interaction. Consequently, the electronic g factor is close to 2 in bulk material.[19] Because the variation of the electron mass with uniaxial pressure is very small in bulk silicon,[20] one can expect that changes in the bulk g factor are small, too.

The enhancement of the g factor in inversion layers has been attributed to many-body interactions.[21] The Zeeman splitting is increased due to exchange and correlation effects and depends on the actual occupation of the spin-split Landau levels, on the line widths, and on the screening. Therefore, a small change in the g factor under uniaxial pressure cannot be excluded. However, a determination of the cyclotron mass under high pressure from the temperature dependence of the SdH oscillations yielded a value of $(0.53 \pm 0.04)m_0$ at an electron concentration of 1.8×10^{12} cm^{-2}. This result shows, that the variation in $\Delta = m^*g/2m_0$ must mainly be attributed to a change in the effective mass. A 180° phase shift of SdH oscillations under pressure (recorded as a function of the gate voltage at a constant magnetic field of 8.6 T) can be explained by an increase of the cyclotron mass to roughly twice its original value. The phase shift can clearly be observed up to electron concentrations of 4.4×10^{12} cm^{-2}. This result seems to disagree with previous data,[7] where a drop in mass from $0.43m_0$ to $0.25m_0$ was observed at about 1×10^{12} cm^{-2} under uniaxial compression of 3.2 kbar. We would like to point out that both sets of data might not be incompatible. In the analysis of the SdH data of Dorda *et al.*[7] only oscillations below 4 T were employed, whereas the phase shift as shown in Fig. 1 was observed at 8.6 T. We are inclined to believe that the cyclotron mass increases with the magnetic field in a pressure range, where the subband energy difference $E_0' - E_0$ is small enough, that interaction occurs, provided that $\hbar\omega$ is comparable with $E_0' - E_0$. This conjecture is supported by the data plotted in Fig. 7 for $P=2.6$ kbar, where a transition seems to occur from the "light electron oscillations" at low magnetic fields to the "heavy electron oscillations" at high B values. Details of magnetic-field effects have recently been discussed by Kelly and Falicov.[22]

The results plotted in Fig. 5 suggest a continuous increase of m_c with pressure. Qualitatively, we expect the same kind of behavior at different magnetic fields. Quantitatively, the pressure, at which coincidence is observed, should shift towards smaller values for higher magnetic fields.

We believe, that our data support the hypotheses, that under uniaxial pressure an interaction between the two subband systems exists. From the data the nature of the interaction cannot be derived, so that is is not possible to decide, whether the electron-phonon interaction, which has been proposed by Kelly and Falicov and which leads to charge-density waves, is realized in silicon inversion layers. It is an open question, whether the electron-phonon interaction in silicon is strong enough, to cause charge-density waves. Nevertheless, it should be noted that the charge-density wave theory can explain a number of puzzling experimental results and that no alternative theory is available at present.

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