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**ABSTRACT**

The transport properties of channel delta-doped quantum well structures were characterized by conventional Hall effect and light-modulated Shubnikov-de Haas (SdH) effect measurements. The large number of carriers that become available due to the delta-doping of the channel, leads to an apparent degeneracy in the well. As a result of this degeneracy, the carrier mobility remains constant as a function of temperature from 300K down to 1.4K. The large amount of impurity scattering, associated with the overlap of the charge carriers and the dopants, resulted in low carrier mobilities and restricted the observation of the oscillatory magneto-resistance used to characterize the two-dimensional electron gas (2DEG) by conventional SdH measurements. By light-modulating the carriers, we were able to observe the SdH oscillation at low magnetic fields, below 1.4 tesla, and derive a value for the quantum scattering time. Our results for the ratio of the transport and quantum scattering times are lower than those previously measured for similar structures using much higher magnetic fields.

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## I. Introduction

Increasing the amount of carrier concentration participating in charge transport leads to an increase in the current density and ultimately to an increase in the power handling capability of a transistor device<sup>1</sup>. In typical high electron mobility transistor (HEMT) structures, the dopant impurities are separated from the charge carriers in the well by an undoped spacer layer. The spatial separation leads to reduced impurity scattering and enhanced low-field mobilities for the charge carriers. The spacer layer however, also limits the amount of carriers transferred to the quantum well and results in incomplete charge transfer<sup>2</sup>. The larger the spacer layer, the smaller the number of carriers transferred to the quantum well to participate in two dimensional transport. This results in a limited power handling capability for the HEMT device.

Originally it was also believed that the high transconductances observed in a HEMT structure were due entirely to the enhanced low-field mobilities of the charge carriers. However, as evidenced by the literature, it is not clear whether these record mobilities translate directly to enhanced high frequency performance or if it is a secondary effect<sup>3,4</sup>. To obtain improved high frequency performance in a transistor, one has to limit the transit time through the device. This can be achieved by either decreasing the gate length or by increasing the velocity of the carriers<sup>5</sup>. As the gate length begins to decrease, the electric field under the gate increases. At this point it is no longer the low field mobility that limits the transistor performance but the high field velocity. For these structures it has been shown that at high electric fields the carrier mobility drops considerably and it is the velocity of the carriers that determines the frequency response of the device. In this case, the extremely high electron mobilities obtained at low electric fields have only a secondary effect on transistor device performance. This is further illustrated by an observed enhancement of the high frequency response in a HEMT structure by reducing the spacer layer width though this reduces the carrier mobility<sup>6</sup>. These findings suggest that the frequency performance of a transistor device may be more dependant on the charge concentration than on the low-field mobility.

In this study we consider several quantum well structures where the doping has been introduced in the center of the channel layer. The physical quantum well consists of a smaller bandgap semiconductor, less than 150Å wide, surrounded on both sides by a larger bandgap

material. For these structures, the dopants and the charge carriers occupy the same region within the channel of the device. Since the dopant impurities are in the well, very large carrier concentrations are possible in these structures. As a result, two-dimensional carrier concentrations of up to  $2 \times 10^{13}/\text{cm}^2$  have been measured in these quantum well structures<sup>7</sup>. While the measured charge concentration in these structures is very large, the mobility of the carriers is low due to a significant amount of impurity scattering. In these structures, the carriers overlap with the ionized impurities and as a result experience a large amount of scattering.

The low carrier mobility observed for these structures restricts the measurement of the oscillatory magneto-resistance (or Shubnikov-de Haas effect) used to characterize the two-dimensional properties of the quantum well. For these structures, the amplitude of the oscillatory magneto-resistance is small and undetectable by the conventional Shubnikov-de Haas (SdH) measurement due to broadening of the Landau levels. In this case, very high magnetic fields are required to characterize the transport properties of the eigenstates using conventional SdH techniques<sup>8,9</sup>. In this paper we demonstrate and present results of an alternative approach to determine the transport properties of the two-dimensional electron gas (2DEG) channel doped structures using a light-modulation technique that allows the characterization at relatively low magnetic fields. The light-modulated SdH technique has been discussed in detail in a previous paper<sup>10</sup>. The technique consists of illuminating the sample with a low intensity laser, in this case a titanium-sapphire (Ti:Sa) laser. The beam is modulated via a chopper which in turn leads to a modulation of the carriers in the sample. The longitudinal voltage is measured by a lock-in amplifier with the reference signal obtained from the chopper. It is this modulation of the carriers that drastically enhances the SdH pattern. Using this technique and digital filtering to separate the components of the waveform, we report on a value of the quantum scattering time obtained at low magnetic fields avoiding localization effects prevalent at higher magnetic fields<sup>11,12</sup>.

The quantum scattering time should not be confused with the transport scattering time. The transport scattering time,  $\tau_b$ , also known as the momentum relaxation time, is the time between scattering events that randomize the direction of the charge carriers. This parameter is obtained from the carrier mobility derived from the Hall effect measurement and is readily available. On the other hand, the quantum scattering time,  $\tau_q$ , sometimes referred to as the

quantum relaxation time, is associated with the broadening of the Landau level. This parameter is the relaxation time within which the energy state of a discrete level can be defined. A value for  $\tau_q$  is obtained from the amplitude dependence of the SdH waveform as a function of magnetic field.

Temperature dependent Hall effect measurements were also carried out to investigate the scattering mechanism acting on the carriers. From the data it is clear that the large doping concentrations in the channel region lead to an apparent degeneracy of the 2DEG. This degeneracy results in a temperature independence of both the carrier mobility and carrier concentration. The temperature independence was observed from 300K down to 1.4K. Based on these results, we proposed and fabricated a field effect transistor (FET) that had device characteristics that remained constant as a function of temperature. This device and its transistor performance are discussed in detail in another paper<sup>13</sup>. For this FET, the gain remained constant as the temperature was lowered from 300K to 70K. This is unlike a typical HEMT structure where the gain increases as the temperature is lowered. This occurs due to lower electron scattering while the carrier concentration changes very little in the 2DEG.

## II. Sample Structures

A cross sectional view of the structures used in this investigation is shown in Figure 1. The physical quantum well in these structures was formed by placing a 150Å small bandgap semiconductor between two larger bandgap materials. Delta-doping of the structures was carried out in the center of the smaller bandgap material. The physical quantum well results in improved carrier confinement and improved output conductance in a transistor device. All of the structures were grown using molecular beam epitaxy (MBE). Structure Q13 consisted of a GaAs channel layer Si delta-doped in the center to a nominal value of  $1.8 \times 10^{12}/\text{cm}^2$ . The channel layer was surrounded on the top and bottom by an undoped  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  layer. Doping of the GaAs layer instead of the  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  limits the effect of persistent photoconductivity (PPC). This effect has been linked to the silicon doping of AlGaAs and the generation of deep energy states known as DX centers<sup>14</sup>. Doping of the GaAs layer also limits the effect of parallel conduction<sup>15</sup>. For these structures, transport occurs primarily in the channel and not in one of the surrounding layers. A 350Å highly doped GaAs layer was grown on the top surface of this structure to improve contact

resistance. This layer is etched away during gate recessing for transistor device fabrication.

Structure Q14 was identical to structure Q13 except that the channel layer was Si delta-doped to a nominal value of  $6 \times 10^{12}/\text{cm}^2$ . The different dopant concentrations were used to determine the effect of the dopant concentration level on the parametric temperature dependence.

Finally, Structure Q15 consisted of a pseudomorphic  $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$  channel surrounded on both sides by undoped  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  layers. The InGaAs channel layer was Si delta-doped in the center to a nominal value of  $6 \times 10^{12}/\text{cm}^2$ . Similar to the previous two structures, a highly doped GaAs layer was grown on the top surface for contact resistivity purposes.

### III. Theory and Experiment

The electronic bandstructure for each sample was analyzed through a self-consistent solution of the Poisson and Schrodinger equations. In Figures 2a,b and c we show the conduction band as a function of depth for structures Q13, Q14, and Q15 respectively. We find that for the higher doped structures, Q14 and Q15, the band bending that results from the large doping concentration is considerably larger than what is observed for the lower doped sample. In fact, the electrostatic potential, associated with the band bending in the larger doped samples, leads to a quantization of an eigenstate. For the lower doped sample, quantization is due entirely to the physical  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}/\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  quantum well. The two higher doped samples have a second eigenstate also associated with the heterojunction barriers. As expected, the ground state energy level of the  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{In}_{0.15}\text{Ga}_{0.85}\text{As}/\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  structure Q15, is lower than that of the similarly doped  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}/\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  structure Q14. This is due to a larger bandgap discontinuity at the  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$  heterojunction compared with the  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}$  interface. The ground subband energy level for structure Q15 is approximately 56 meV lower than that of structure Q14. The difference is even greater compared with the lower doped sample Q13 which is approximately 146meV. The large value of the eigenstate energies relative to the Fermi level result in a temperature independence of the carrier mobility and carrier concentration in the 2DEG. This is discussed further in the following section.

The two-dimensional properties of the carriers in the quantum well were investigated by light-modulated SdH measurements. Developed by Schacham et al.<sup>10</sup>, the technique consists of

injecting a light source onto the sample surface in order to modulate the carriers inside the quantum well. The experimental setup is a conventional SdH measurement with an additional lock-in amplifier and a chopped laser. The injected light beam is modulated by the chopper which in turn leads to a modulation of the carriers in the sample. The longitudinal voltage is measured by a lock-in amplifier with the reference signal obtained from the chopper. It is this modulation of the carriers that drastically enhances the SdH pattern. The theory behind this amplitude enhancement of the oscillatory amplitude is as follows.

The oscillatory resistivity  $\Delta\rho_{xx}$  for a two subband system is given by the following expression<sup>16</sup>

$$\frac{\Delta\rho_{xx}}{\rho_0} = A_1 \frac{\Delta g_1}{g_0} + A_2 \frac{\Delta g_2}{g_0} + B_{12} \frac{\Delta g_1 \Delta g_2}{g_0^2} \quad , \quad (1)$$

where  $g_0$  is the zero-field density of states,  $A_1$  and  $A_2$  are the amplitudes of oscillations for the ground and first excited subbands respectively, and  $B_{12}$  represents the intermodulation term. Describing the broadening of the Landau levels due to scattering by a Lorentzian of half-width  $\Gamma$ , the oscillatory density of states,  $\Delta g_i$ , can be written as a Fourier expansion

$$\Delta g_i = 2g_0 \sum_s D_T(sX) \exp\left(\frac{-s\pi}{\omega_c \tau_{qi}}\right) \cos\left(\frac{\hbar \pi n_i}{qB} + s\pi\right) \quad , \quad (2)$$

where  $\tau_q (= \hbar/2\Gamma)$  is the quantum scattering time,  $D_T(X) = X/\sinh(X)$  with  $X = 2\pi^2 kT/\hbar\omega_c$ , and  $I=1,2$  denotes the different subbands. For the above expression  $k$  is Boltzmann's constant,  $T$  is temperature, and  $\omega_c$  is the cyclotron frequency,  $\omega_c = qB/m^*$ . The change in the oscillatory resistivity due to modulation of the carriers is obtained from the derivative of equation (1) with respect to the concentration in the subbands,  $n_1$  and  $n_2$ . The derivatives of equation (1) with respect to  $n_1$  and  $n_2$  are given by

$$\delta \left( \frac{\Delta \rho_{xx1}}{\rho_o} \right) = \left[ \left( \frac{\partial A_1}{\partial n_1} + \frac{\partial B_{12}}{\partial n_1} \frac{\Delta g_2}{g_o} \right) \frac{\Delta g_1}{g_o} + \left( \frac{A_1}{g_o} + B_{12} \frac{\Delta g_2}{g_o^2} \right) \frac{\partial \Delta g_1}{\partial n_1} \right] \delta n_1 \quad , \quad (3)$$

$$\delta \left( \frac{\Delta \rho_{xx2}}{\rho_o} \right) = \left[ \left( \frac{\partial A_2}{\partial n_2} + \frac{\partial B_{12}}{\partial n_2} \frac{\Delta g_1}{g_o} \right) \frac{\Delta g_2}{g_o} + \left( \frac{A_2}{g_o} + B_{12} \frac{\Delta g_1}{g_o^2} \right) \frac{\partial \Delta g_2}{\partial n_2} \right] \delta n_2 \quad . \quad (4)$$

The total change in the oscillatory resistivity due to light-modulation is obtained from the sum of equations (3) and (4) and is given by

$$\delta \frac{\Delta \rho_{xx}}{\rho_o} = \delta \frac{\Delta \rho_{xx1}}{\rho_o} + \delta \frac{\Delta \rho_{xx2}}{\rho_o} \quad . \quad (5)$$

The excess concentration generated through illumination,  $\delta n_T$ , is distributed between the two subbands  $\delta n_1$  and  $\delta n_2$ . The enhancement of the oscillation occurs through the multiplication of the oscillation amplitude by the excess carrier concentration,  $\delta n_1$  and  $\delta n_2$ . Since the concentration in each eigenstate increases as a function of illumination, the amplitude of each of the subbands increases proportionately.

A further enhancement of the SdH oscillation occurs through the derivative of the density of states. The derivative is given by

$$\frac{\partial \Delta g_i}{\partial n_i} = 2g_o D_T(X) \exp \left( \frac{-\pi}{\omega_c \tau_{qi}} \right) \left[ \frac{\pi}{\omega_c \tau_{qi}} \frac{\partial \tau_{qi}}{\partial n_i} \cos \left( \frac{\hbar \pi n_i}{qB} + \pi \right) + \frac{\hbar \pi}{qB} \sin \left( \frac{\hbar \pi n_i}{qB} \right) \right] \quad , \quad (6)$$

where we have taken only the first Fourier component  $s = 1$  to describe the oscillations. Since  $\omega_c = qB/m^*$ , both terms in the square brackets are multiplied by the inverse of the magnetic field,  $1/B$ . This leads to a considerable enhancement of the oscillations at low magnetic fields. It is this experimental derivative effect that enables the observation of the SdH oscillations at much lower magnetic fields as compared to the conventional measurement technique.

A final enhancement of the oscillatory amplitude occurs through the derivative of the quantum scattering time. As the concentration in the well is increased by illumination,  $\tau_q$  increases sharply due to a gain in the electron's energy which reduces localization effects (i.e., resonant scattering)<sup>17,18</sup>. The overall enhancement of the SdH waveform through light-modulation should be compared with the technique of differentiating with respect to the magnetic field<sup>19</sup>. Taking the derivative with respect to  $B$  results in a multiplication of the oscillation amplitude by the carrier concentration in the subbands,  $n_i$ . This is different from the light-modulation technique where the waveform is multiplied by the excess carrier concentration. For the case of magnetic field differentiation, since  $n_1 \gg n_2$ , that technique greatly enhances the signal due to the ground subband.

#### IV. Results and Discussion

Hall bars were fabricated on the three samples and the carrier mobilities and concentrations were measured as a function of temperature for each structure. The results are shown in Figure 3. From the figure we see that for the two higher doped samples Q14 and Q15, the mobility remains constant throughout the temperature range. For the lower doped sample, Q13, there is a very slight decrease in the mobility below 125K. The fact that the mobility remains constant for the two higher doped structures and drops only slightly for the lower doped structure would suggest a reduced role for the temperature dependence in impurity scattering. For nondegenerately doped structures, where the dominant scattering mechanism is due to impurity scattering, the low field mobility is proportional to  $T^{3/2}$ . This equation is valid for temperatures below 100K. Below this temperature, the thermal energy governs the Coulomb interaction between the carriers and the charged ions. As the temperature is lowered, the atoms of the cooler lattice are less agitated and lattice scattering is less important; however, the thermal

motion of the carriers is also slower. Since a slowly moving carrier is likely to be scattered more strongly by an interaction with a charge ion than is a carrier with greater momentum, impurity scattering events cause a drop in mobility with decreasing temperature.

In degenerately doped semiconductors, as is the case in our samples, the carriers in the quantum well will have a kinetic energy orders of magnitude larger than the thermal energy. The kinetic energy of the carriers is given by the difference between the Fermi energy,  $E_F$ , and the eigenstate energy of the occupied subband,  $E_n$ . For structure Q15, the calculated eigenstate energy of the ground subband relative to the Fermi level is equal to 190meV. At a temperature of 4K the thermal energy of the carriers is equal to  $k_B T/q = .344\text{meV}$ . Even at 300K, the thermal energy is only equal to 25.9meV which is much smaller than the calculated kinetic energy of the carriers. The same was true of the two other structures. Thus in these degenerate systems, the temperature independent Fermi velocity is much larger than the thermal velocity and the mobility is expected to remain constant throughout the temperature range as was evident in our structures. From Figure 3 we see that the carrier concentration also remained constant as a function of temperature for the three structures due to the degeneracy.

Following the Hall effect analysis, the two-dimensional properties of the carriers inside the quantum well were then investigated by light-modulated SdH measurements. Since the doping was introduced in the GaAs channel layer and not the AlGaAs barrier layer where DX centers can be generated<sup>20</sup>, the three samples had only a negligible amount of persistent photoconductivity (PPC). Of the three, only the lower doped GaAs channel structure had an apparent increase in the concentration due to photoconductivity (PC). For this sample, the concentration increased approximately by 10% after illumination. Once the illumination was removed, the photogenerated carriers recombined and the carrier concentration returned to its zero illumination value. The structures were illuminated using a variable wavelength titanium-sapphire (Ti:Sa) laser operating in the visible region. As was indicated earlier, the light-modulated SdH technique is based on measuring the change in the magneto-resistance due to carrier generation by a modulated light source. Because only the lower doped sample showed any apparent increase in concentration with illumination at the available laser intensity, the light-modulated SdH measurement was carried out only on this sample. The difference in the measured carrier concentrations for the

lower doped sample and the two higher doped samples is significant,  $2 \times 10^{12}/\text{cm}^2$  versus  $9 \times 10^{12}/\text{cm}^2$ . Therefore to obtain the same increase in the excess concentration as observed in the lower doped sample, the higher doped samples have to be illuminated with a larger intensity light source. One has to be careful though to maintain a low optical injection level where the transport mechanism is only perturbed and not completely altered as in the photo-Hall effect measurement<sup>21</sup>.

Shown in Figure 4 is the longitudinal voltage as a function of magnetic field for the lower doped GaAs channel sample prior to light-modulation at 4K. We see from the figure that the measured longitudinal voltage decreases only slightly as a function of magnetic field. From this lack of magneto-resistance in the curve, we can conclude that most of the carriers are found in a single conduction path, in this case, the quantum well region. Also from the figure we see that even at the largest magnetic field, 1.4T, there is no evidence of an oscillatory magneto-resistance associated with the SdH effect. Observation of the SdH oscillations in a conventional measurement requires that the thermal energy broadening,  $kT$ , and the scattering-induced energy broadening,  $\hbar/\tau_q$ , be smaller than the Landau level spacing in the quantum well,  $\hbar\omega_c$ . This requires that the SdH measurement be carried out at low temperatures and that the mobility of the sample be relatively high<sup>22</sup>. The upper limit of the temperature is dictated by  $\hbar\omega_c > kT$  which translates to  $T < 1.3B/(m^*/m_0)$  kelvin. The limit on the mobility is determined from  $\hbar\omega_c > \hbar/\tau_q$  and is equivalent to  $\mu > 10^4/B$  ( $\text{cm}^2/\text{V}\cdot\text{s}$ ) where  $B$  is in tesla. The limit on  $\mu$  was obtained by assuming that the quantum scattering time is equal to the transport scattering time,  $\tau_p$ , and using the well known relation  $\mu = q\langle\tau_p\rangle/m^*$ . When these conditions on the temperature and mobility are not met, the amplitude of the oscillation is small and virtually undetectable by the conventional SdH technique. However, by light-modulating the carriers, the SdH waveform is greatly enhanced due to the differentiation and multiplication of the oscillation by the excess carrier density in the well. In Figure 5a, we show the SdH waveform obtained by light-modulating the carriers with a low intensity Ti:Sa laser. Here, the longitudinal voltage is plotted as a function of magnetic field from 11kG to 14kG. The oscillation observed in this waveform corresponds to the ground subband and confirms the two dimensionality of the charge carriers. In Figure 5b, the waveform was digitally filtered with a bandpass filter to remove both the high-frequency noise and the DC

component associated with background subtraction and zero magnetic field normalization. From the period of the oscillations we can obtain an accurate value of the carrier concentration for each of the occupied subbands. A fast Fourier transform (FFT) of the oscillations for both the ground and first excited subbands yields a two dimensional concentration of  $2.1 \times 10^{12}/\text{cm}^2$  and  $5.3 \times 10^{11}/\text{cm}^2$  respectively. The sum of these concentrations coincides well with our Hall measured value of  $2.7 \times 10^{12}/\text{cm}^2$ .

From the oscillatory component of the SdH waveform we can also obtain a value of the quantum scattering time. Both the quantum and transport scattering times provide a measure of the scattering effects or the mean free time between collisions. The transport scattering time,  $\tau_b$ , corresponds to the electric field response and is derived from the Boltzmann equation and Drude relations. In this case,  $\tau_b$  is weighted by a factor of  $(1 - \cos\theta)$  and is determined mostly by large angle scattering. The resultant mobility is related to the average over the entire electron distribution and is given by the equation noted earlier,  $\mu = q\langle\tau_b\rangle/m^*$ . A value of this scattering time is obtained experimentally by a measurement of the drift or Hall mobility. Unlike  $\tau_b$ , the quantum scattering time effectively measures the entire collision cross section. For a discrete level, the broadened Landau level width  $\Gamma$ , as determined from the uncertainty principle, is given by  $1/\tau_q = \hbar/2\Gamma$ .

The quantum scattering time can be obtained from the half-width of the FFT amplitude peak of the SdH waveform<sup>23</sup>. However, the value of  $\tau_q$  derived using this technique depends to a large extent on the range of magnetic field and the number of data points used in the FFT. A more common approach is based on the magnetic field dependence of the amplitude of the SdH oscillation. The quantum scattering time is obtained by a least-squares fit of the amplitude of the oscillation peaks at a fixed temperature. The SdH waveform is fit to the expression for the oscillatory magneto-resistance shown in equation (2) using only the first Fourier component,  $s=1$ , and replacing the zero-field density of states,  $g_0$ , with  $(C\omega_c^2 \tau_l^2)/(1 + \omega_c^2 \tau_l^2)$  where  $C$  is a constant of the equation<sup>14</sup>. Several other pre-factors have been suggested in the literature<sup>24,25</sup>. However, we have found that the numerical value of the quantum scattering time derived from the fit depends very little on this parameter. For the least-squares fit we use a value of the transport scattering time obtained directly from the Hall measurement. This value of  $\tau_b$  may be different for

each of the subbands. The value obtained from the measurement is therefore an effective value of  $\tau_i$  for the two populated subbands.

For the low doped GaAs channel structure, we obtained a value of  $0.8 \times 10^{-13}$  (sec) for  $\tau_i$ . Using this value, a best fit of the oscillatory data obtained by the light-modulated SdH measurement to equation (2) yields an approximate value of  $2.2 \times 10^{-13}$  (sec) for the ground subband quantum scattering time. The ratio of the two scattering parameters,  $\tau_i/\tau_q$ , is equal to 0.36. A ratio of  $\tau_i/\tau_q$  between 0.5 and 1.0 is indicative of isotropic short range scattering for which the scattering cross section is independent of angle. The lower value of  $\tau_i/\tau_q$  observed for this structure could be attributed to a possible backscattering of the carriers by ionized impurities inside the quantum well<sup>26</sup>. Our results differ to those of Harris et al.<sup>8</sup>, where very large magnetic fields were used to obtain a value of the quantum scattering time for a similar channel delta-doped structure. Their magneto-transport measurements were carried out to 8T compared with 1.4T used in this investigation. They obtain a value of 2.0 for the ratio of the scattering times. The difference in the two ratios may be due to a magnetic-field dependence of the scattering cross-section. As the magnetic field is increased, the cyclotron orbits of the Landau quantization become narrower<sup>27</sup>. This may lead to an increase in small angle scattering and to a decrease in the quantum scattering time. This dependence of  $\tau_q$  on the magnetic field is consistent with the results obtained by Fang et al.<sup>28</sup> for an  $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}/\text{GaAs}$  HEMT structure. Because of the high mobility of the carriers in their structure, SdH oscillations were observed at the lower magnetic fields. They derive a value for  $\tau_q$  from the slope of the magnetic field dependence of the magneto-resistance oscillation amplitude (the so called Dingle plot) for a magnetic field range of .7T-5T. The slope being proportional to  $1/\tau_q$ . From their experimental data (see their Figure 4), it is clear that there is a shift in the slope as the magnetic field is increased beyond approximately 1.4T. The slope of the curve at the lower magnetic field range is smaller, corresponding to a larger quantum scattering time compared to the scattering time at higher magnetic fields.

Finally, we should point out that our structure differs from an unconfined delta-doped GaAs layer where the quantization occurs only due to the electrostatic potential associated with the heavy doping<sup>29,30</sup>. In our structure, the carriers are physically confined in two dimensions by the AlGaAs/GaAs/AlGaAs heterostructure. This confinement of the carriers may prevent the

charge transport from being completely isotropic and independent of the scattering angle. The scattering taking place in this sample is also different from what is observed in typical HEMT structures. In a HEMT structure, the dominant scattering mechanism is generally a long range potential that produces predominantly small angle scattering. In that case, the transport scattering time is larger than the quantum scattering time by a factor of 10 or more<sup>31</sup>.

## V. Conclusion

The transport properties of channel delta-doped quantum well structures were characterized using conventional Hall effect and light-modulated SdH effect measurements. The large number of carriers that become available due to the delta-doping of the channel result in an apparent degeneracy in the charge density. This degeneracy leads to a temperature independence of both the carrier mobility and the carrier concentration. Since the carriers are located in the same channel region as the dopants, the carrier mobility was low due to a large amount of ionized impurity scattering. This restricted the measurement of the oscillatory magneto-resistance used to characterize the 2DEG. However, by modulating the carriers through illumination we were able to observe the SdH effect oscillation at relatively low magnetic fields, 1.4 tesla. Using this technique, we obtain a value for the ratio of the transport and quantum scattering times that is significantly lower than previously measured for similar structures using higher magnetic fields. We attribute the difference to a localization of the cyclotron orbits at the higher magnetic fields.

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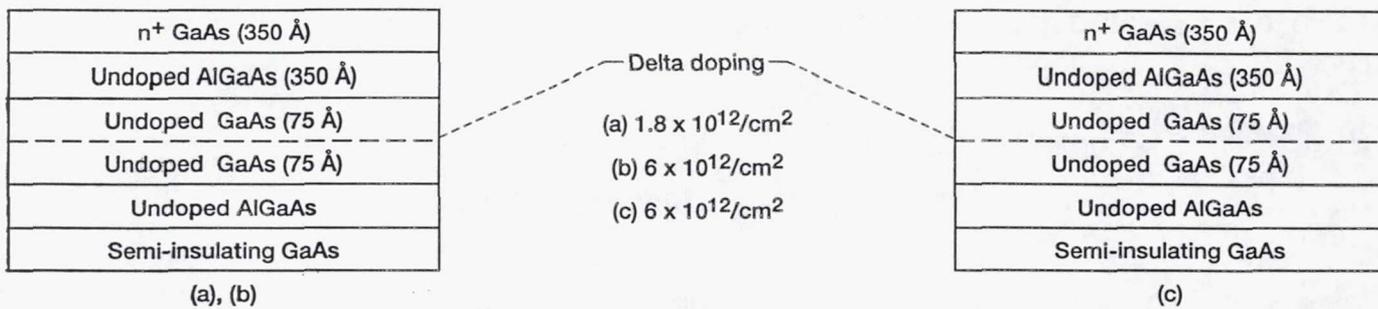


Figure 1.—Schematic cross-section with nominal dimensions (not to scale) for samples. (a) Q13. (b) Q14. (c) Q15.

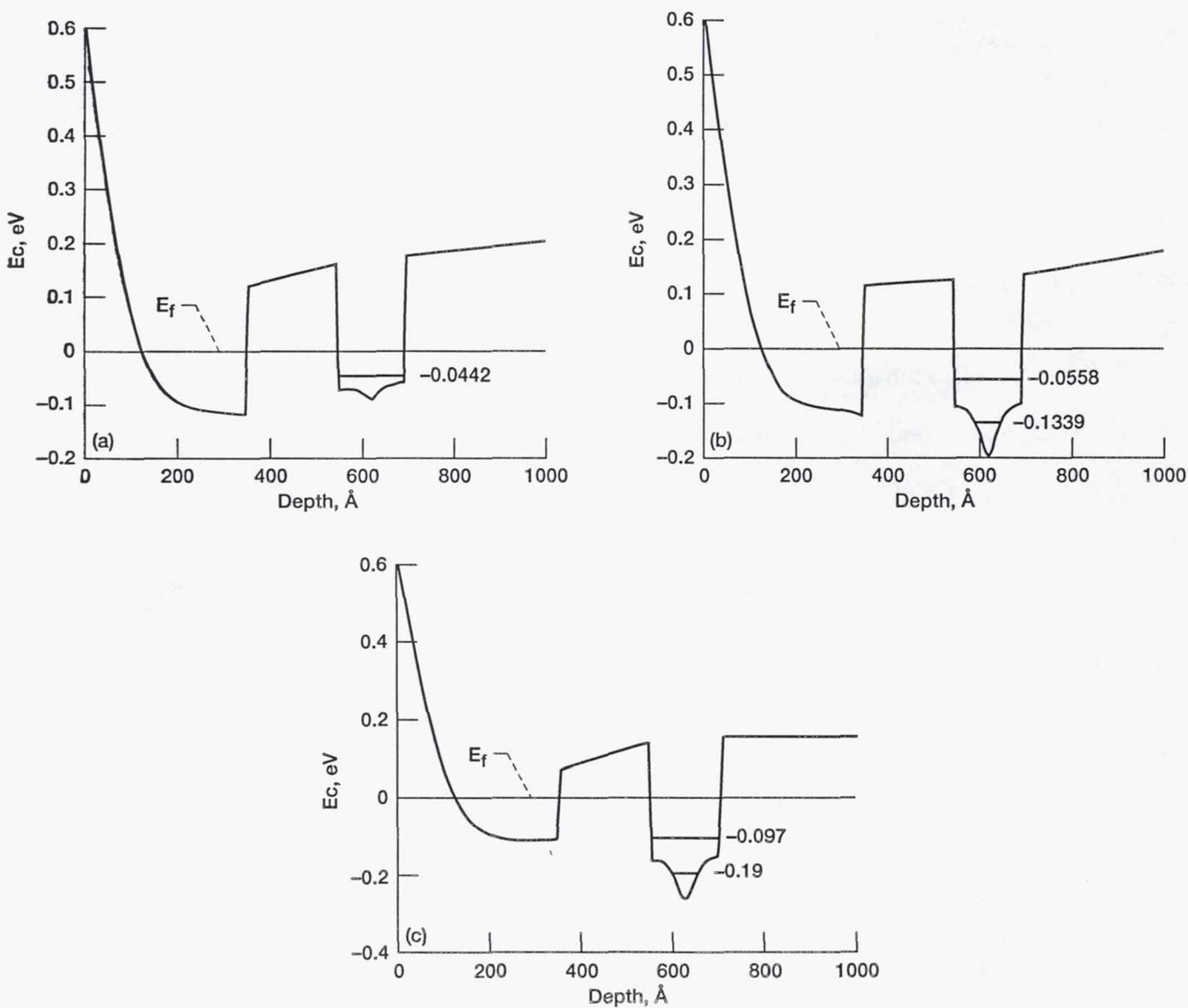


Figure 2.—Self-consistent simulation of the energy band structure of structures. (a) Q13. (b) Q14. (c) Q15.

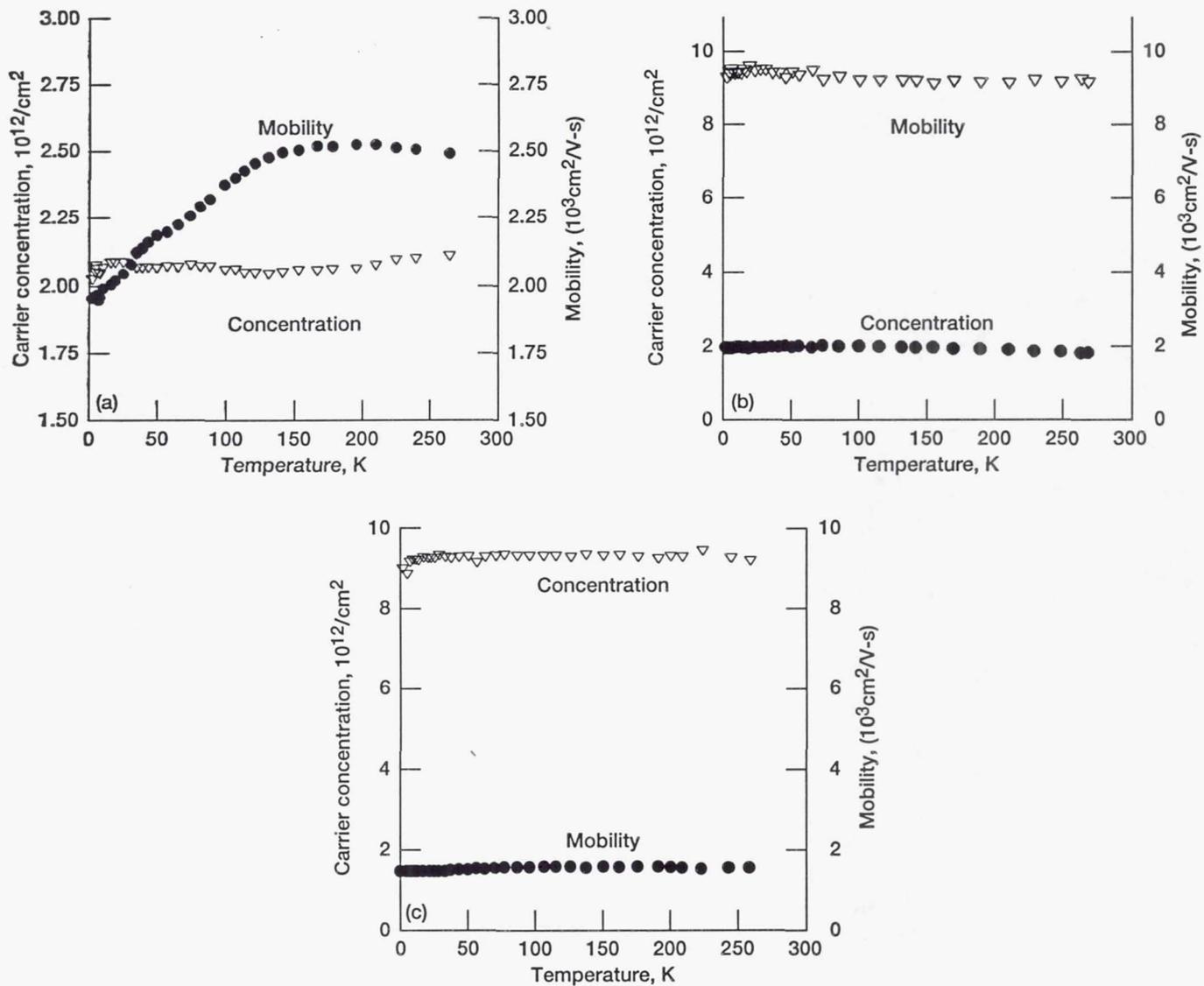


Figure 3.—Hall carrier concentration and mobility as a function of temperature for structures. (a) Q13. (b) Q14. (c) Q15.

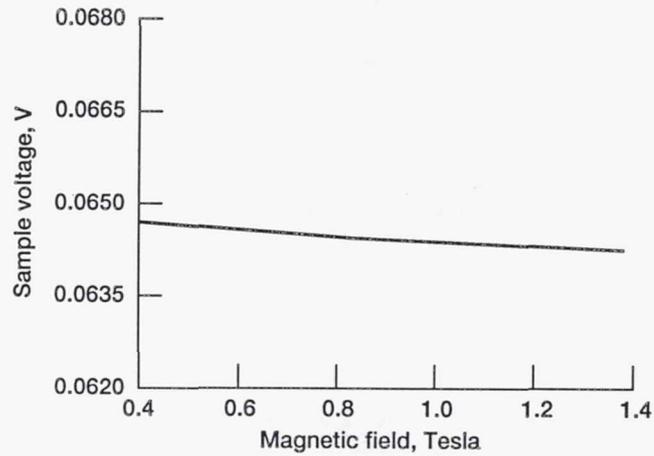


Figure 4.—Longitudinal voltage as a function of magnetic field prior to light modulation for structure Q13 measured at 4K.

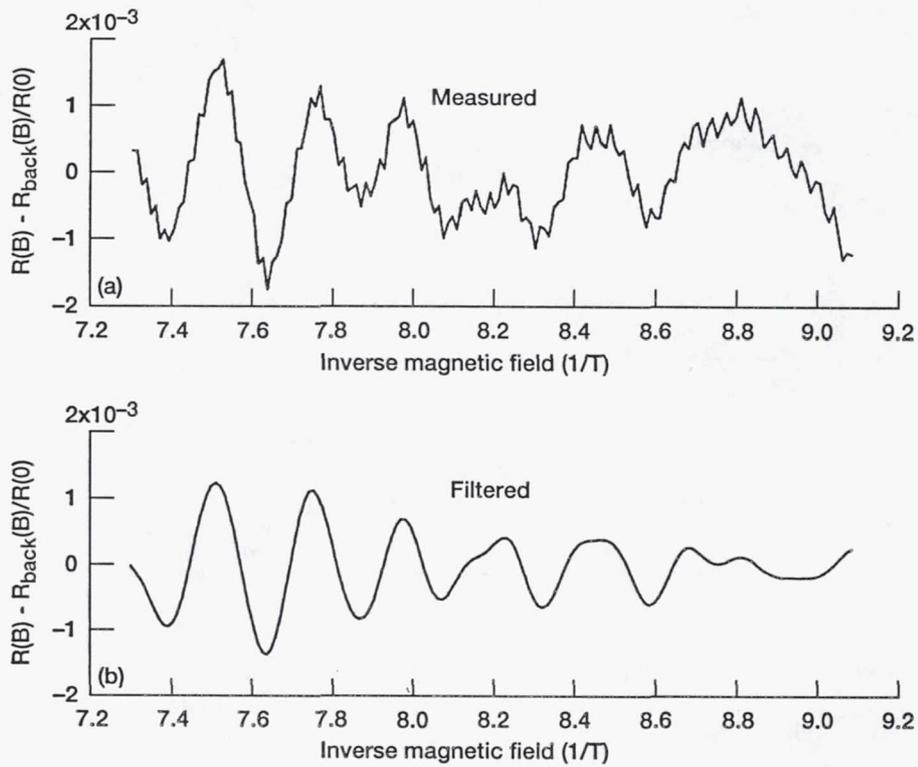


Figure 5.—Light-modulated SdH data for the ground subband. (a) Before digital filtering. (b) After digital filtering measured at 4K.

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