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ABSTRACT

In this study we investigate both the transport and quantum scattering times as a function of the carrier concentration for a modulation doped $Al_{0.3}Ga_{0.7}As/GaAs$ structure. Carriers in the well are generated as a result of the persistent photoconductivity effect. When more than one subband becomes populated, digital filtering is used to separate the components for each of the excited subbands. We find that the quantum scattering time for the ground subband increases initially as the carrier concentration is increased. However, once the second subband becomes populated, the ground subband scattering time begins to decrease. The quantum scattering time for the excited subband is also observed to decrease as the concentration is increased. From the ratio of the transport and quantum scattering times, it is seen that the transport in the well becomes more isotropic also as the concentration is increased.

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To increase the power handling capability of a high electron mobility transistor (HEMT) structure, the charge concentration in the channel has to be increased to very high levels[1]. The large charge densities result in the population of excited subbands that may lead to a deterioration of the carrier mobility[2]. Thus, to optimize the design of these high density structures, one needs to understand the relationship between the carrier concentration and the mobilities of the carriers in the subbands. To date it is still not clear whether the mobilities of the excited subbands are larger or smaller than that of the ground subband[3,4]. Even less is understood about the relative mobility of the subbands as a function of the carrier concentration. Mobility of the carriers is dependent on the scattering mechanisms that are present[5]. A measure of the scattering effects, or the mean free time between collisions, is given by the transport and quantum scattering times. In this study we investigate these scattering parameters as a function of carrier concentration generated as a result of the persistent photoconductivity effect. When second subband population occurs, digital filtering is used to separate the parameters associated with each of the different subbands.

The transport scattering time, τ_t, corresponds to the electric field response and is derived from the Boltzmann equation and Drude relations. In this case τ_t is weighted by a factor of (1-cosθ) and is given by $1/\tau_t = \int dk' W_{kk'}(1-\cos\theta)$, where $W_{kk'}$ is the probability of scattering from state k to k' and θ is the scattering angle. The resultant mobility is related to the average over the entire electron distribution and is given by the well known relation $\mu = q<\tau_t>/m^*$. A value for this scattering time is generally obtained experimentally by a measurement of the drift or Hall mobility. Because of the weighting factor, this scattering time is determined mostly by the large angle scattering. On the other hand, the quantum scattering time, which is associated with the quantum mechanical Landau level broadening, effectively measures the entire collision cross section. The expression for the quantum scattering time, τ_q, is given by $1/\tau_q = \int dk' W_{kk'}$. For a discrete level, the broadened Landau level width Γ, as determined from the uncertainty principle is given by $1/\tau_q = \hbar/2\Gamma$.

Experimentally, the quantum scattering time can be derived from the amplitude of the

Subnikov-de Haas (SdH) oscillation of the longitudinal resistivity measured as a function of magnetic field. The equation for the oscillatory resistivity amplitude was derived by T. Ando et. al.[6] and depends on the transport and quantum scattering times and the effective mass of the carriers. The expression is shown in Eq. (1), where T is the electron temperature, E_F is the Fermi energy, and ω_c is the cyclotron frequency, $\omega_c = eB/m^*$. The subscript i refers to the different subbands.

$$\rho_{xx_i}(osc) = \frac{C(\omega_c\tau_t)^2}{1+(\omega_c\tau_t)^2}\left[\frac{X}{\sinh(X)}\right]\exp\left[\frac{-\pi}{\omega_c\tau_{q_i}}\right]\cos\left(\frac{2\pi E_{F_i}}{\hbar\omega_c}\right) \qquad (1)$$

$$X = 2\pi^2 kT/\hbar\omega_c$$

The quantum scattering time can be obtained from a least-squares fit of the amplitude of the various peaks at constant T with τ_q as the single adjustable parameter in Eq. (1). Finally, from the period of the SdH oscillation we can obtain an accurate value of the subband concentration.

Using the SdH and Hall techniques we measured both scattering times, τ_t and τ_q, for a modulation doped $Al_{0.3}Ga_{0.7}As/GaAs$ structure as a function of carrier concentration using digital filtering to separate the components for the ground and the excited subbands. The MBE-grown structure consisted of a GaAs channel with an $Al_{0.3}Ga_{0.7}As$ barrier, Si delta doped to a nominal value of 1.0×10^{18} /cm^3 . The doping and the channel were separated by a 50 Å undoped $Al_{0.3}Ga_{0.7}As$ spacer layer. The structure was epitaxially lifted-off from its GaAs growth substrate and attached to a semi-insulating quartz substrate. This procedure is discussed in detail in a previous paper[7]. By use of the persistent photoconductivity effect we were able to gradually increase the concentration inside the well. The sample was exposed to white light illumination for short periods of time. After each illumination cycle, the longitudinal resistivity was measured as a function of magnetic field. The sample was illuminated to a

point of saturation where no new carriers were generated.

A typical plot of the measured longitudinal voltage after illumination is shown in Figure 1. The sample had a large amount of magneto-resistance, associated with a parallel conducting path in the doped spacer layer[8]. By fitting the longitudinal resistivity to a two-carrier model we can obtain a value for μ_{2D}, $\mu_{parallel}$, n_{2D}, $n_{parallel}$. Later we will use this value of μ_{2D} to obtain the transport scattering time. Using the fitted values of the longitudinal resistivity, we subtracted the background from the SdH oscillation and normalized it to the low field value as shown in Figure 2a. It is clear from the figure that the higher frequency oscillation which is due to the ground subband, is being amplitude modulated by a slower frequency corresponding to an excited subband. Using digital filtering we can separate the components of each subband. Here the data was analyzed using a Butterworth infinite impulse response filter with the order of the filter dependent on the filter specifications. These specifications include passband ripple, stopband attenuation and transition width. Phase distortion of the original waveform during filtering is eliminated by time reversing and doubly filtering the signal. In Figure 3a we show the low frequency component obtained by filtering the signal with a lowpass filter. Similarly in Figure 3b, we show the high frequency component obtained using a highpass filter. In Figure 2b we sum the lowpass and the highpass components and compare with the original waveform. We see from the figure that there is very little difference in the two waveforms. The filtered data was then fitted to the oscillatory component of the SdH waveform. The solid lines shown in Figure 3 correspond to the fitted data having a standard deviation of less than 10^{-4}.

Following this procedure, the carrier concentration and quantum scattering time for each subband were determined throughout the illumination cycle at 4.2K. The carrier concentration was obtained from the period of oscillation of the SdH waveform and τ_q was determined directly from the fit to the data. The carrier concentration as a function of illumination in arbitrary units is shown in Figure 4. The arbitrary units refer to the experiment number where one unit of illumination is equivalent to one illumination cycle. The intensity of the

light source remained the same for each cycle but the time of illumination varied. From the figure we see that the second subband became populated after only the fourth cycle of illumination. We also see that the concentration increased in each of the subbands; however, the increase in the ground subband was larger than that of the first excited subband.

The quantum scattering time is also plotted in Figure 4. Since both the quantum scattering time and the carrier concentration are plotted together, we can easily relate the two parameters. From the figure we see that the quantum scattering time for the ground subband, τ_{q0}, increases sharply with only a small increase in the concentration. This is consistent with the theoretical results of Isihara and Smrcka[9]. At low concentrations, τ_{q0} increases steeply as a function of concentration as the energy of the electrons increases and becomes larger than the localization energy at the bottom of the conduction band. At this point the electrons are influenced less by the resonant scattering due to localization. After the initial increase, τ_{q0} levels off and begins to gradually decrease. However, the final value of τ_{q0} is still 37% larger than that of zero illumination. The decrease occurs at the point where second subband population becomes evident. Thus, the drop in τ_{q0} may be due to the added scattering mechanism (i.e., inter-subband scattering) that takes place as the second subband becomes populated. It may also be due, based on the results of Isihara and Smrcka, on an enhancement of the impurity scattering. As the Fermi level increases it forces the electrons to the AlGaAs/GaAs interface where they come into closer contact with the scattering impurities, resulting in an enhancement of the small angle scattering. They predict a much sharper drop than what we observe. This may be due to the undoped spacer layer in our structure that separates the carriers from the scattering impurities. In the structure that they modelled, the scattering centers were adjacent to the inversion layer.

The quantum scattering time for the excited subband, τ_{q1}, was obtained for the final three cycles of the illumination. We were unable to obtain values for the other cycles due to a limited number of slow frequency oscillations within the range of magnetic field. The few oscillations made it impossible to obtain an accurate fit of the longitudinal oscillatory term.

We found that the final value of τ_{q1} was 1.3 times larger than τ_{qo} at the same point of illumination. These results are consistent with those obtained by other groups[3]. Similar to τ_{qo}, we see from the figure that τ_{q1} also decreases with an increase in concentration.

As indicated earlier, this sample had a considerable amount of magneto-resistance due to a parallel conducting layer in the doped AlGaAs region. By fitting this magneto-resistance to a two-carrier model at the lower concentrations we were able to obtain values for μ_{2D} and $\mu_{parallel}$. We continued to use this two-carrier model at the higher concentrations where second subband population became evident. Because of the similarities in the two subband mobilities and the large difference in the mobilities between the carriers in the well and those in the parallel conducting path (generally a few orders of magnitude) a fit to a three-carrier model would not have been feasible. Therefore, at the higher concentrations, where second subband population takes place, we obtain an effective value of the 2D mobility, $\mu_{2D,eff}$, from the magneto-resistance fit. The $\mu_{2D,eff}$ is a combination of the carrier mobilities in the two subbands. Having obtained a value of the mobility for the carriers in the well, we can derive a value for the transport scattering time, τ_t. As with mobility at the higher concentrations, the transport scattering time will consist of an effective value due to the two subbands being populated. In Figure 5 we plot the three ratios τ_t/τ_{qo}, $\tau_{t,eff}/\tau_{qo}$, $\tau_{t,eff}/\tau_{q1}$ as a function of the total concentration in the well.

Initially there is a sharp drop in the τ_t/τ_{qo} ratio as the concentration is increased. There is a large discontinuity as we go from τ_t/τ_{qo} to the $\tau_{t,eff}/\tau_{qo}$ ratio once the second subband becomes populated. The discontinuity probably results from the introduction of a new scattering channel as well as from a contribution to the value of $\tau_{t,eff}$ by the carriers in the second subband. We see however, that $\tau_{t,eff}/\tau_{qo}$ continues to decrease as the concentration is increased. The same holds true for the $\tau_{t,eff}/\tau_{q1}$ ratio of the excited subband. The final value at saturation of $\tau_{t,eff}/\tau_{qo}$ is 6.3 . The decrease in the ratios would indicate that transport within the well is becoming more isotropic. Thus short range scattering, for which the scattering cross section is independent of the angle, is becoming more prominent and is no longer as

strongly peaked in the forward direction.

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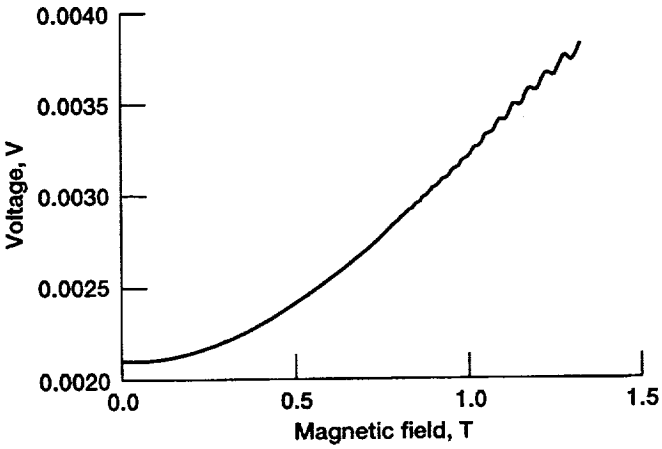

Figure 1.—Typical SdH data measured at 4.2 K under illumination.

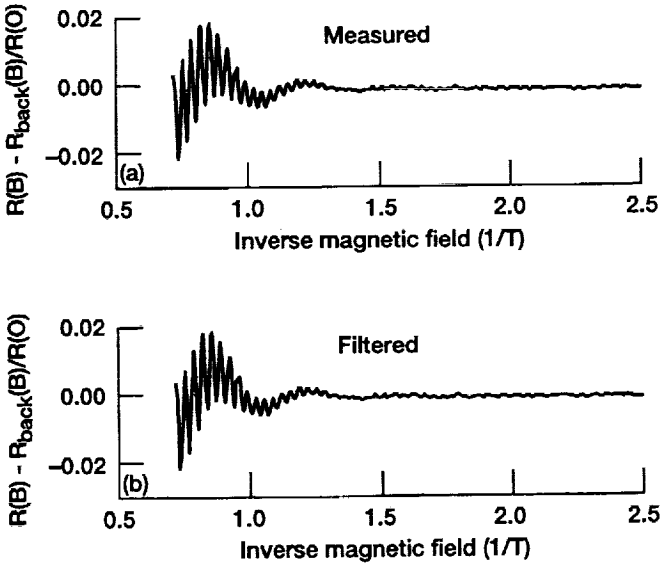

Figure 2.—(a) SdH resistivity data with background subtraction and normalization to low field value prior to filtering. (b) Reconstruction of original SdH waveform before filtering by adding the lowpass and highpass components.

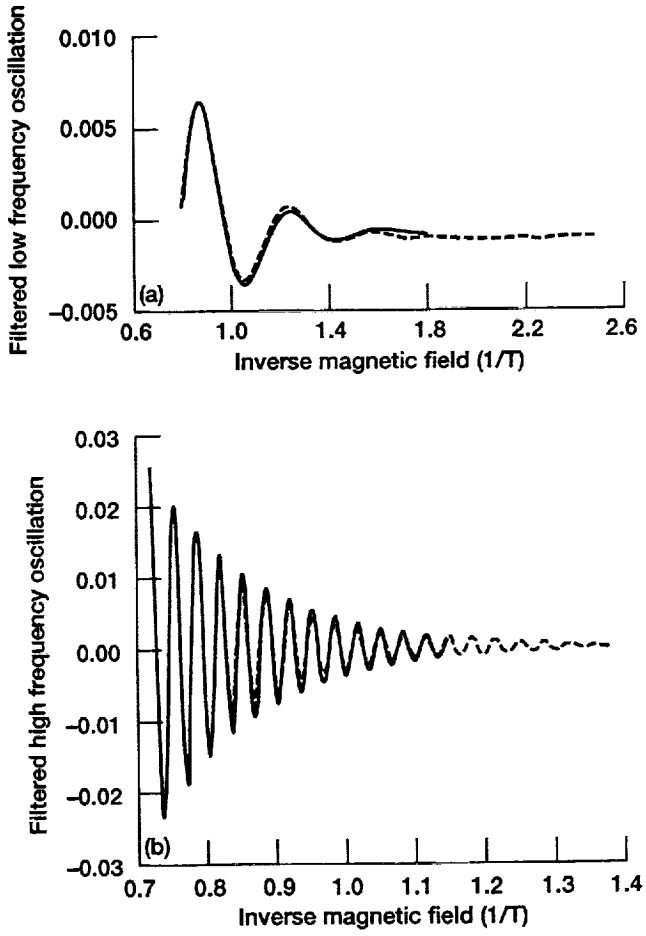

Figure 3.—(a) Lowpass and (b) highpass filtering of the SdH waveform after background subtraction. The dotted and solid lines represent the filtered and fitted data respectively.

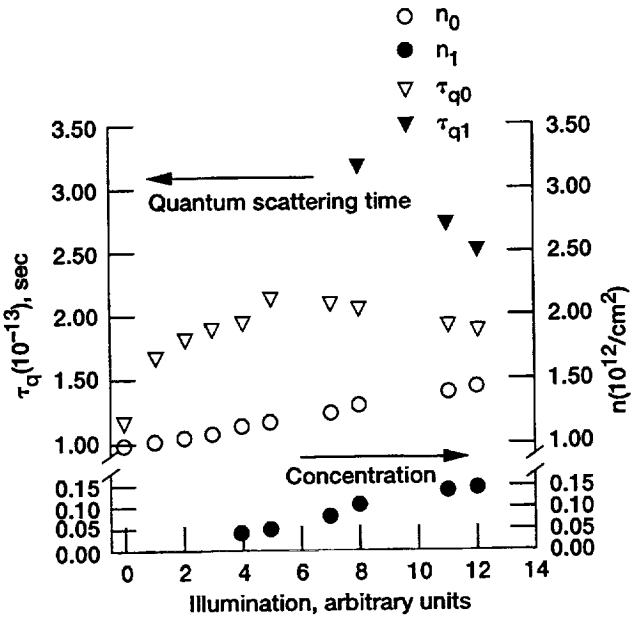

Figure 4.—Carrier concentrations n_0, n_1 and quantum scattering times τ_{q0}, τ_{q1} for both the ground and excited subbands as a function of white light illumination.

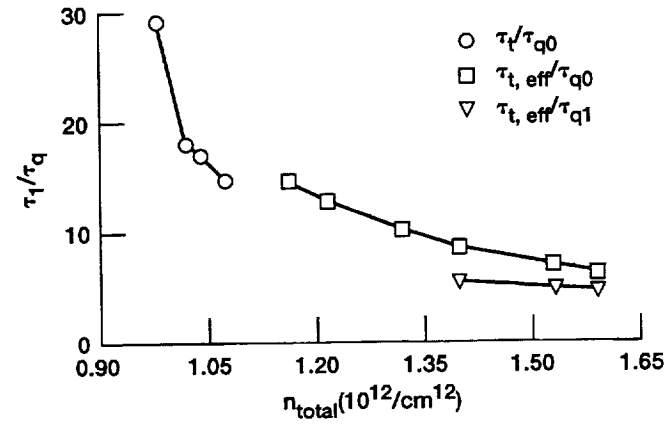

Figure 5.—Ratio of the transport and quantum scattering times for the ground and excited subbands as a function of the total concentration in the well. $\tau_{t,\,eff}$ is the effective transport scattering time when second subband population occurs.

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13. ABSTRACT (*Maximum 200 words*)

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