Abstract—We present a detailed study of the transport in GaAs/Al$_x$Ga$_{1-x}$As modulation-doped structures in the low field and high magnetic field quantum limit for varying amounts of parallel conduction in the AlGaAs region. We observe the apparent breakdown of quantum Hall effect behavior due to low mobility carriers in the parallel channel. The onset of conduction through the parallel channel by quantum transport measurements has been observed, along with a non-linear dose dependence due to photoexcitation.

I. INTRODUCTION

Quantized Hall resistance and the simultaneous zero diagonal resistance state of two-dimensional carriers is now a well-documented phenomenon in a number of systems [1]-[3]. This phenomenon, occurring at low temperature and high magnetic field, is characterized by the experimental fact of the Hall resistance $\rho_{xy}$, becoming quantized in units of $\hbar/e^2$ where $\hbar$ is Planck’s constant and $e$ is the electronic charge. When $\rho_{xy}$ takes on quantized values of $\hbar/e^2$, the diagonal resistivity $\rho_{xx}$ approaches zero in the limit $T \to 0$. The quantum number $i$ is an integer for integral quantization, which can be understood within the framework of an independent particle picture [4], [5]. The quantum number can also take on fractional values [6], [7], which is believed to arise from the condensation of the 2D carriers into a highly correlated fluid-like ground state [8].

Since the first observation of the integral quantum Hall effect in the two-dimensional electron gas (2DEG) of a Si–MOSFET inversion layer [1], the phenomenon has been studied in numerous embodiments of 2D carrier systems. The systems that have attracted the most attention are the compound heterojunction epitaxial structures, in particular the GaAs/Al$_x$Ga$_{1-x}$As systems [2], due to the lattice match of the constituents. The perfection of these heterojunction systems has allowed the achievement of extremely high carrier mobilities by the modulation doping technique [9]. The quantum Hall effect has been seen in numerous III–V compound systems and recently in a II–VI system [3].

The modulation doping technique, while instrumental in achieving high electron mobilities, is also responsible for an effect called persistent photoconductivity (PPC) [10]. This effect is characterized by a light-induced conductivity enhancement that persists for long times (in some systems, $\geq 10^8$ s) at low temperatures. The PPC has been attributed to the excitation of electrons out of deep donor-related traps in the AlGaAs, known as DX centers, which suppress recapture due to large lattice relaxation [11]. In the GaAs/Al$_x$Ga$_{1-x}$As system, these excited electrons are able to maintain quasi-equilibrium with the 2D layer in the GaAs [12], forming a parallel conduction path in the Al$_x$Ga$_{1-x}$As.

The PPC in GaAs/Al$_x$Ga$_{1-x}$As modulation-doped structures has been utilized by a number of authors [3], [13]-[15] to modulate the carrier density when studying quantum transport. Although PPC has been studied in the GaAs/Al$_x$Ga$_{1-x}$As system by a number of workers [16]-[18] none of these studies has explored the effects of PPC on the behavior of the 2DEG in the quantum limit. Here we present a detailed study of PPC effects on the quantum transport coefficients in a high-mobility GaAs/Al$_x$Ga$_{1-x}$As modulation-doped structure. The measurements are compared to low field values of the transport coefficients to derive information concerning density, mobility, and the distribution of carriers in the 2DEG and parallel conduction path.

II. THEORY

Let us first consider single carrier conduction for two parallel media in the absence of any quantum transport phenomena. Let us also define the media by the index $i (=1, 2)$. Under the influence of a mutually perpendicular electric field $E$ and magnetic field $B$, we can express the conductivity tensor for media $i$ as

$$\sigma = \frac{n_i e^2}{m_i^*} \begin{bmatrix} \tau_i & -\omega_c \tau_j^2 \\ \frac{\omega_c^2 \tau_i^2}{1 + \omega_c^2 \tau_i^2} & \frac{1 + \omega_c^2 \tau_i^2}{1 + \omega_c^2 \tau_i^2} \end{bmatrix}$$

where $n_i$ is the carrier density, $e$ is the electronic charge, $m_i^*$ is the effective mass, $\omega_c$ is the cyclotron frequency.
and \( \tau_i \) is the scattering time. For simplicity, we consider a single relaxation time \( \tau_i \) for the carriers in media \( i \).

Now, the total conductivity of the two-component system can be expressed as a sum of the individual conductivity tensors:

\[
\sigma = \begin{bmatrix}
\frac{\tau_1}{1 + \omega_i^2 \tau_1^2} & \frac{\tau_2}{1 + \omega_i^2 \tau_2^2} \\
\frac{\omega_i^2 \tau_1^2}{1 + \omega_i^2 \tau_1^2} & \frac{\omega_i^2 \tau_2^2}{1 + \omega_i^2 \tau_2^2}
\end{bmatrix}
\]

The measured quantities of interest are usually the components of the resistivity tensor. These quantities are the Hall resistivity \( \rho_{xy} \) and the magnetoresistance \( \rho_{xx} \). We can find these quantities by inverting (2), whereupon

\[
\rho_{xx} = \frac{\tau_1}{1 + \omega_i^2 \tau_1^2} + \frac{\tau_2}{1 + \omega_i^2 \tau_2^2}
\]

and

\[
\rho_{xy} = \frac{-\omega_i \tau_1^2}{1 + \omega_i^2 \tau_1^2} + \frac{-\omega_i \tau_2^2}{1 + \omega_i^2 \tau_2^2}
\]

To specialize, let us define media 1 as the 2DEG at the GaAs/Al\(_{1-x}\)Ga\(_x\)-As heterojunction interface, and media 2 as the Al\(_{1-x}\)Ga\(_x\)-As. For this situation, we shall assume that the mobility of the carriers in the 2DEG, \( \mu_1 \), is much greater than the mobility in the parallel conduction path, \( \mu_2 \).

It is convenient to define the low magnetic field and high magnetic field limits of these general expressions. At low magnetic field \((\omega_i \tau_1 \text{ and } \omega_i \tau_2 \ll 1)\), we have

\[
\rho_{xx} = \frac{1}{n_1 e \mu_1 + n_2 e \mu_2}
\]

and

\[
\rho_{xy} = \frac{n_1 \mu_1^2 + n_2 \mu_2^2}{e[n_1 \mu_1 + n_2 \mu_2]} B
\]

where we have made the substitution \( \tau_i = \mu_i m_i^* / e \). Both components of the resistivity tensor in the low field limit are dominated by the contribution of the high-mobility region.

Similarly, in the high field limit \((\omega_i \tau_1 \text{ and } \omega_i \tau_2 \gg 1)\), we have

\[
\rho_{xx} = \frac{n_1 + n_2}{\mu_1 \mu_2}
\]

and

\[
\rho_{xy} = B \frac{e}{e[n_1 + n_2]}
\]

shown (by going to the frame of reference \( cE \times B/B^2 \)) that \( \rho_{xy} = ne \mu_1 B \), which does not exhibit a quantized density. To explain the experimental observations of the quantum Hall effect requires the existence of localized states in the tails of each Landau level subband. When the Fermi level resides in these localized states, which cannot carry any current at \( T = 0 \), the remaining extended states of the filled Landau levels automatically adjust to carry the entire Hall current. These current-carrying extended states cannot scatter due to their wide separation in energy from any empty states. Thus, the diagonal resistivity vanishes, i.e., \( \rho_{xx} = 0 \). Since the density of these current-carrying states does not change with \( B \) as long as the Fermi level resides in the localized states, the carrier density \( n_i = i \) where \( i \) is the (integral) number of filled Landau subbands whose density \( n = eB/h \). Substituting this into (8), the Hall resistivity of the 2DEG in the quantum limit is given by

\[
\rho_{xy} = \frac{h}{4e^2},
\]

which is the quantized resistance in units of 25, 813 \( \Omega \).

The experimental result is a step structure in the Hall resistance versus magnetic field or carrier density, normally controlled by a gate voltage. An alternative to gate modulation of carrier density is to photoexcite carriers into the 2DEG from traps. The concurrent effect of this modulation technique is the subject of the present investigation.

Let us now consider the presence of a media \((\text{Al}, \text{Ga}_{1-x} \text{As})\) parallel to the 2DEG. Prior to any phot-
to excitation, we shall assume that the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is depleted, although it contains deep level complexes known as DX centers [11]. Electrons photoexcited from the DX centers remain in the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ conduction band for a long time because their recapture by the ionized donors is impeded by a microscopic potential barrier. These free electrons transfer to the 2DEG channel (either by tunneling through the interface barrier or through the ohmic contacts) and thus add to the 2DEG density [16]–[18]. However, as the number of photoexcited carriers increases, the effective doping concentration increases [16].

As a consequence, the depletion widths at the surface and at the heterojunction interface, which are inversely proportional to the effective doping concentration, become smaller upon photoexcitation. Preliminary investigations of this effect have been reported [16], [19]. However, the transition from a depleted to a conducting barrier region has not been investigated in detail.

To consider the case of parallel conduction through this barrier region, we will assume that media 2 cannot support a 2DEG. Substituting (9) into (8) for the case of mixed conduction, we have for the Hall resistivity in the high field and quantum limit

$$\rho_{xy} = \frac{B}{e^n + \frac{i eB}{h}}$$

where the integer $i$ again takes on the appropriate quantized values. These values of the Hall resistivity will deviate (specifically, decrease) from the well-defined quantized values upon the onset of parallel conduction. Similarly, we can see from (7) that the diagonal resistivity will remain vanishingly small in the quantum limit until carriers populate the parallel conduction band. This effect has important consequences in the use of quantum Hall effect as a resistance standard or as a method for determining the fine structure constant. A high precision measurement of $\rho_{xx}$ simultaneous with the "standard" $\rho_{xy}$ values puts a limit on the number of carriers in the parallel conduction path, and thus a limit on the deviation of $\rho_{xy}$ from the standard values.

III. EXPERIMENTAL PROCEDURE

The samples studied were modulation-doped GaAs/$\text{Al}_0.3\text{Ga}_{0.7}\text{As}$ heterostructures grown in a Riber 2300 MBE on a Cr-doped GaAs substrate. The epitaxial layers consisted of a 1 $\mu$m nominally undoped GaAs buffer layer followed by a 150 Å $\text{Al}_0.3\text{Ga}_{0.7}\text{As}$ spacer layer and 500 Å of Si-doped $\text{Al}_0.3\text{Ga}_{0.7}\text{As}$. The samples were then fabricated into Hall bridges using standard photolithographic techniques. The minimum channel width used in these studies was 150 $\mu$m to exclude any localization effects due to short channel effects [20]. The samples were mounted onto ceramic flatpacks for lead strain relief.

The samples were cooled slowly (~30 h) from room temperature to low temperature in a light-tight container to eliminate residual PPC and to minimize thermally induced strain. Low field values of the mobility and carrier density were measured at $T = 1$ K, and found to be $\mu = 10^3$ m$^2$/V·s and $n = 2.8 \times 10^{15}$ m$^{-2}$, respectively.

The quantum transport measurements were taken between 20 mK and 7.0 K in a dilution refrigerator using a 7.8 T superconducting solenoid to apply magnetic fields perpendicular to the sample. Temperature measurements were made using a $^3$He melting curve thermometer. Transport measurements were made by pulsing a dc current source and averaging voltages for positive and negative current polarities to eliminate thermal EMF problems. Excitation current amplitudes ranged from 10 mA to 5 $\mu$A. The pulse sequence consisted of a 650 ms positive pulse, a 5 ms off period, a 650 ms negative pulse, and a 500 ms settling period. Depending on the temperature range, the sequence period ranged from 5 to 30 s to avoid any Joule heating of the charge carriers.

Light excitation was made by direct illumination from a GaAsP/GaAs red LED. Light dose was controlled by varying the time the LED was activated by a constant (20 mA) current. Dose quantities reported in this paper refer to the calculated number of photons arriving at the sample. For our particular experimental configuration, there were approximately $7.8 \times 10^{11}$ photons/s striking the sample surface. The photon dose was varied up to an empirically saturated dose value. No attempt has been made to correct for possible reflection of photons at the sample surface nor for absorption in the sample; thus, absolute intensity figures must be viewed cautiously. However, relative dose values reported here were easy to control and are thus highly precise.

IV. RESULTS AND DISCUSSION

Quantum Hall resistance plateaus corresponding to Landau level filling factors down to $i = 2$ have been observed in these structures. Fig. 1 shows the Hall resistance $\rho_{xy}$ and the diagonal magnetoresistance $\rho_{xx}$ at $T = 75$ mK for a sample cooled under dark conditions and before any photoexcitation by the LED source. The Hall plateaus agree with the theoretical quantized values to within the resolution (dynamic range) limitations of the apparatus; specifically, for the $i = 4$ plateau, we have $\rho_{xy}\text{(experimental)} = 6453 \pm 12 \Omega$, whereas $\rho_{xy}\text{(theoretical)} = 6453 \Omega$. The minima in the magnetoresistance could be resolved to within $\pm 0.05 \Omega$ for $\rho_{xx}$ values less than 1 $\Omega$.

Fig. 2 shows $\rho_{xy}$ as a function of magnetic field as the photoexcitation dose is varied, and Fig. 3 shows $\rho_{xx}$ as a function of magnetic field for the same photon doses used in Fig. 2. The measurements were taken sufficiently long after excitation and at approximately the same time after photoexcitation to eliminate possible transient and nonexponential decay effects of the PPC [10]. The photon doses ranged from a minimum of $3.9 \times 10^9$ photons to $2.5 \times 10^{13}$ photons. There was no temperature cycling or temperature variation between the sets of measurements. We clearly observe the systematic shift of the quantum Hall plateaus (and the accompanying magnetoresistance min-
ima) toward higher magnetic field as the density of carriers in the 2DEG increases. We observe the full development of some less-developed plateaus that were weak (i = 5) or nonexistent (i = 7) at lower magnetic fields. The effect is more apparent for the odd-integer plateaus since the spin energy is smaller than the Landau energy at these field values. Upon reaching a critical photon dose (>7.8 × 10^{11}), quantum transport apparently breaks down, and the plateaus deviate from the expected values. At the same time, the magnetoresistance minima rise significantly above zero.

The density of carriers as a function of light dose was determined in two ways: by the high field values of the Hall resistance (n = B/ερ_{xy}), either by extrapolating through the apparent Hall plateau centers or choosing the value at a single plateau center, and by the periodicity of the Shubnikov-deHaas (SdH) oscillations in ρ_{xx} [i.e., n = 2e/hΔ(1/B)]. This is shown in Fig. 4(a). The departure of these two methods of determining the carrier density becomes apparent at a dose of 1.6 × 10^{12}, which is the same dose at which the quantum transport clearly deviates.

Referring to (8), we see that the high field Hall resistance method gives the combined carrier density in both the 2DEG and the Al_{1-x}Ga_{x}As, whereas the oscillations in ρ_{xy} are essentially measuring the 2DEG carrier density. If true, the carrier density determined from the low field Hall resistance values as predicted from (6) should agree...
well with the method using the SdH oscillations in $\rho_{xx}$. The comparison in Fig. 4(b) shows excellent agreement. It should be noted that magnetic freeze-out effects \cite{21}, which would occur at $-6$ T, are not evident since both the low and the high field limits are the same [Fig. 4(a) versus Fig. 4(b)] until the onset of parallel conduction.

Once we have determined the electron distribution in the two regions, we can also determine the mobility of the electrons in the Al$_x$Ga$_{1-x}$As. Choosing a photon dose of $2.5 \times 10^{13}$, we have $n_1$ (2DEG) = $5.5 \times 10^{15}$ m$^{-2}$ and $n_2$ (Al$_x$Ga$_{1-x}$As) = $7.5 \times 10^{15}$ m$^{-2}$. Using (7) in the quantum limit, we get $\mu_2 = 0.19$ m$^2$/N·s. It should be noted that the condition $\omega_c \tau > 1$ is not yet completely satisfied in the Al$_x$Ga$_{1-x}$As since the magnetoresistance background is still increasing, so the mobility may be slightly higher than this value.

A sensitive test to determine when conduction starts in the Al$_x$Ga$_{1-x}$As region is to observe the deviations of the $\rho_{xx}$ values from the quantized values, as predicted by (8). Fig. 5(a) shows the values of the $i = 4$ plateau as a function of photon dose. The onset of parallel conduction is again clear for a dose $>7.8 \times 10^{11}$. We can define the limits of conduction in the Al$_x$Ga$_{1-x}$As by observing the minima in $\rho_{xx}$, as shown in Fig. 5(b). Using the value for the mobility in the Al$_x$Ga$_{1-x}$As derived above and our resolution limit of 0.05 $\Omega$, the carrier concentration in the Al$_x$Ga$_{1-x}$As region for photon doses up to $7.8 \times 10^{11}$ is found from (7) to be $< 4 \times 10^{10}$ m$^{-2}$. Bridge techniques used by other workers \cite{22} have measured minimum resistances in these regions to be $< 10^{-7}$ $\Omega$. From this, it is possible to put an upper limit on the number of carriers

\begin{equation}
\langle n \rangle < 1 \times 10^9 \text{ m}^{-2}.
\end{equation}

In this photoexcitation phenomenon. The dynamics of
this process clearly deviates from present understandings [3, 23] of the detailed photoexcitation mechanisms, implying a more complicated rate equation model. However, the microscopic model interpretation of DX centers as the responsible traps [11] in the Al$_x$Ga$_{1-x}$As is still consistent with our results.

V. Summary

We have done a systematic study of the low field and quantum transport coefficients in a GaAs/Al$_x$Ga$_{1-x}$As modulation-doped heterostructure. We find that the onset of conduction through a parallel path in the Al$_x$Ga$_{1-x}$As is readily observable via quantum transport measurements. These measurements allow us to determine the distribution of carriers in the 2DEG and in a parallel path. We can also use the measurements to put limits on the perturbation of the quantized resistance values due to a parallel conduction path.

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References


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