Solid State Communications, Vol.41, No.10, pp.707-709, 1982. Printed in Great Britain.
0038-1098/82/100707-03$02.00/0 Pergamon Press Ltd.

OBSERVATION OF INTERSUBBAND SCATTERING IN A 2-DIMENSIONAL ELECTRON SYSTEM

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(Received 10 September 1981 by A. G. Chynoweth)

We observe a strong increase in the low temperature electron scattering rate of a 2-dimensional electron gas in a modulation doped GaAs-(AlGa)As heterojunction at the transition from one-subband to two-subband conduction. Our data provide direct evidence for the occurrence of intersubband scattering processes. Electron densities as well as mobilities in each subband are determined separately throughout the transition regime. Mobilities of the ground subband considerably exceed those of the excited subband. All features of the calculated density dependence of the mobilities are qualitatively reproduced by our data.

Electron transport properties of 2-dimensional (2D) systems have been studied extensively, experimentally as well as theoretically, during the last decade.[1] The inversion layer on a silicon surface, where the electron motion normal to the surface is quantized into a sequence of electric subbands, (see Fig. 1) represents the most widely employed physical realization of the 2D concept. There have been numerous investigations of the electron transport in this system. At low temperatures two mechanisms have been isolated to contribute to the electron scattering[2]: ionized-impurity scattering and surface-roughness scattering. It has also been predicted that scattering of electrons between subbands should occur when more than one electron subband is occupied.[3,4,5].

The most characteristic signature of this intersubband scattering is an abrupt reduction of electron mobility whenever a subband starts to become populated[3,4]. So far there has been no experimental evidence for this discontinuous behavior.

Recently a new class of 2D electron systems was introduced, where more than one subband can readily be occupied[6]. The electron concentration of these modulation-doped GaAs-(AlGa)As heterojunctions is conveniently variable over a finite range by an external electric field applied to an electrode attached to the backside of the specimen.[7] In a properly designed heterojunction this configuration allows one to sweep the carrier concentration and in turn the Fermi level continuously through the transition from one-subband population to two-subband population. It therefore represents an ideal system for the investigation of the predicted scattering mechanism.

The sample was prepared by molecular beam epitaxy[8] on an insulating (Cr-doped) [100] GaAs substrate. It consists of an 1μm thick undoped GaAs layer covered by ~600Å thick $Al_{0.22}Ga_{0.78}As$ layer doped with Si to a level of $\sim 2\times10^{18}cm^{-3}$. Electrons from the Si-donors of the (AlGa)As in the vicinity of the junction transfer across the interface to the lower conduction band states of the GaAs layer forming a highly mobile quasi 2D electron gas bound to the interface via the Coulomb attraction of the ionized impurities across the junction[6].

Standard bridges were photo-lithographically defined (see insert Fig. 2). Contacts were made by alloying Indium into the layers at 400°C for 1 min. A copper plate glued to the backside of the sample served as an electrode to vary the carrier concentration of the 2D electron gas in the bridge.

Hall as well as magneto-resistance measurements (Shubnikov-deHaas effect) were performed at 4.2K in the dark with the magnetic field normal to the 2D plane. The samples were cooled down slowly in the dark (~ 10 min from 300K to 4.2K) to avoid temperature gradients across the specimen.

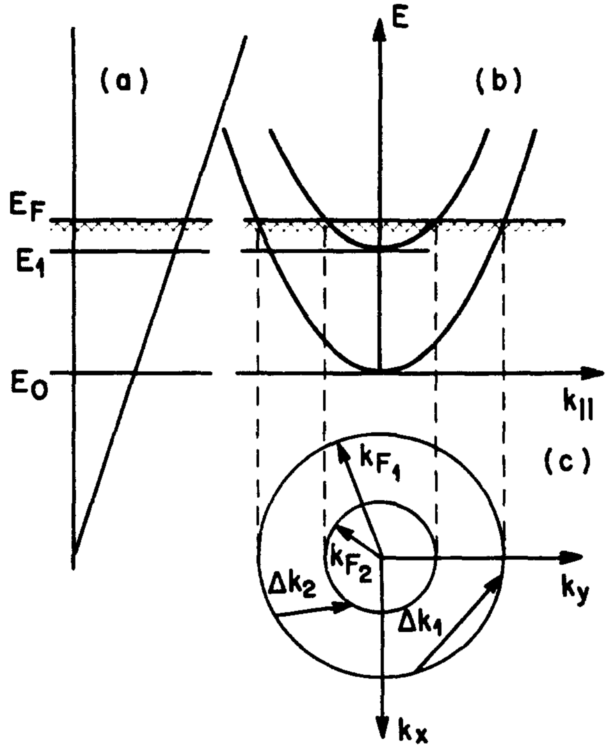

Fig. 1 Schematic representation of electric subband formation (E_0,E_1) in a triangular potential (a) in-plane dispersion relation (b) and Fermi circles (c) of a 2D electron gas. E_F is the Fermi level, k_{F_1} and k_{F_2} are Fermi wave vectors of ground subband and excited subband respectively. k_x,k_y and $k_{||}$ are in-plane wave vectors. Two energy conserving electron scattering mechanisms are indicated: standard intra-subband scattering (Δk_1) and the observed inter-subband scattering (Δk_2).

Fig. 2 shows magneto-resistance data for 3 different gate voltages -600V, OV, +200V. While the -600V data exhibit a single oscillation indicative of the population of a single electric subband, the +200V data clearly is composed of two

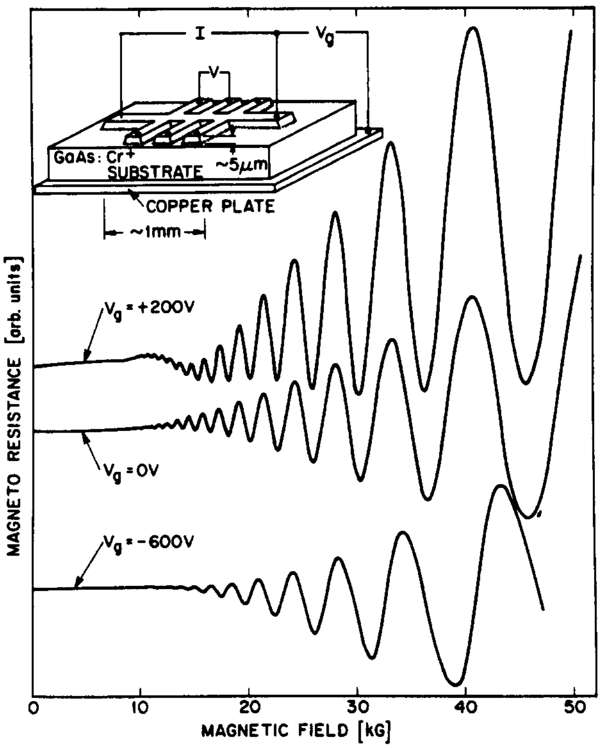

Fig. 2 Magneto-resistance data of the 2D electron gas for 3 different gate voltages V_g. For V_g=200V a second oscillation is clearly observed indicating the population of the first excited subband. The inset shows the sample geometry, the bridge, the backside electrode (copper plate), current (I) and voltage (V) connections.

oscillations of different periods indicating the occupation of a second subband. The existence of a second oscillation in the OV data is ambiguous. The electron concentration $n = 2e/hc\,\Delta(1/H)$ (hc/e=flux quantum) in the subbands obtained from the oscillation periods $\Delta(1/H)$ in reciprocal field is shown in Fig. 3a for a large number of fixed gate voltages. For gate voltages between -600V and -200V only the ground-subband is occupied and its carrier concentration n_1 is linear in gate voltage. Above −100V its carrier concentration determined from the oscillation period remains constant. For voltages above 80V the occupation of a second subband up to a density n_2 is unambiguously observed. The total density $n_s=n_1+n_2$ remains linear in gate voltage, as expected from a simple capacitor model which applies to our insulating gate geometry.[7]

We, therefore, can interpolate the data for n_s and infer the occupation n_2 of the second subband between -200V and +80V where magneto-oscillation of the second subband is not accesible.

The magneto-resistance data demonstrate that this system allows us to vary the carrier concentration of the 2D system continuously through the transition region from one subband occupation to two subband occupation. Moreover, they provide a table for the absolute and relative population of the subbands.

In order to investigate electron scattering as a function of density and subband population we performed standard Hall and conductivity (σ) experiments simultaneously with the magneto-resistance measurements. Figs. 3b and 3c show the phenomenological result for the Hall density n_H and Hall mobility $\mu_H=\sigma/n_He$ for a large number of fixed gate voltages. Both curves experience a break in an otherwise smooth gate voltage dependence near the onset of occupation of the second

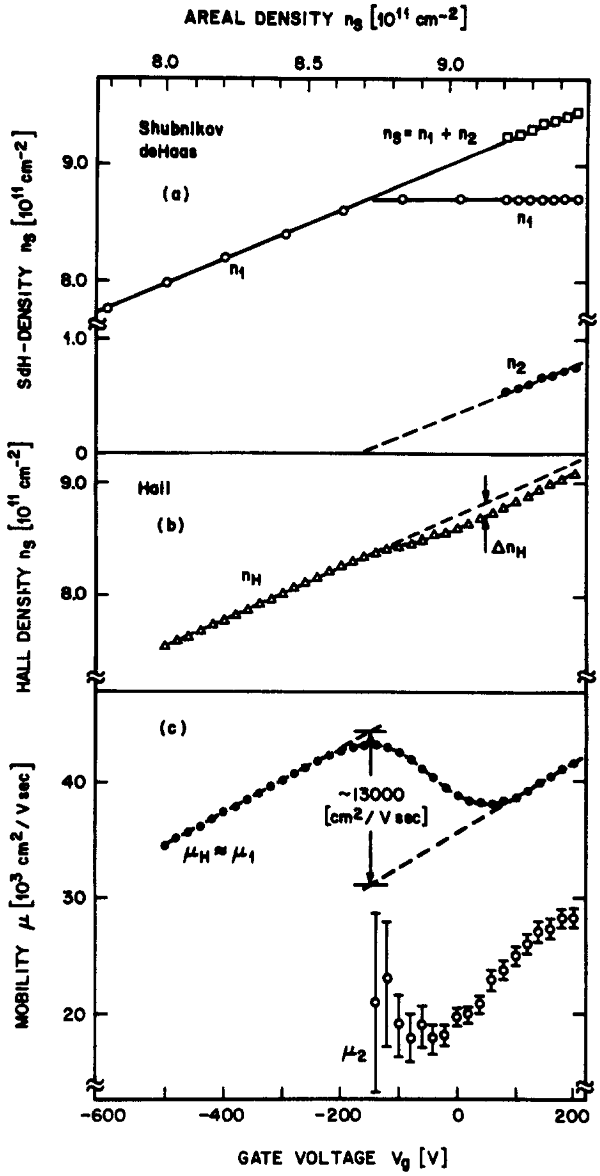

Fig. 3 (a) Gate voltage (V_g) dependence of the densitites in each subband μ_1 and μ_2 as determined by magneto-resistance data (SdH-effect) (see Fig. 2) (b) V_g - dependence of the Hall density μ_H. (c) V_g - dependence of the Hall mobility μ_H and the mobilities of the ground subband μ_1 and the excited subband μ_2. The top scale reproduced the SdH-densities. μ_1 and μ_2 are calculated from $\mu_H, \Delta n_H$ and n_2 using equations 5 and 6.

subband. This discontinuity has not been observed in samples where a second subband could not be occupied.[7] Consequently, we interpret the drop in mobility as the onset of intersubband scattering which increases the scattering rate for the 2D carriers.

The Hall density n_H is linearly dependent on gate voltage but experiences a reduction Δn_H simultaneously with the drop in mobility for higher gate voltages. Notice that already in the one band conduction regime n_H does not coincide with n_s. This discrepancy results from a slight density gradient over our specimen as was confirmed by measuring different pairs of side arms of the bridge. A slight density gradient will affect the Hall data as well as the Shubnikov-deHaas pattern. However, as the gradient is small and as our considerations are based on the deviation Δn_H this discrepancy is immaterial. The reduction Δn_H in Hall density obviously is connected with two band conduction. A simple calculation for the Hall density n_H and Hall mobility μ_H of a system consisting of 2 types of carriers having densities n_1 and n_2 and mobilities μ_1 and μ_2 but the same effective mass yields:

$$\mu_H = \frac{n_1\mu_1^2 + n_2\mu_2^2}{n_1\mu_1 + n_2\mu_2} \quad (1) \;, \quad n_H = \frac{n_1\mu_1 + n_2\mu_2}{\mu_H} \quad (2)$$

Only for $\mu_1 = \mu_2$ will a Hall experiment measure the total carrier density $n_s = n_1 + n_2$. The deviation Δn_H clearly indicates that the scattering rates of the two carriers are different. In order to determine the relative mobilities we solve equs. (1) and (2) for μ_1 and μ_2 and obtain.

$$\mu_1 = \frac{\mu_H n_H}{n_1 + n_2}\left[1 + \sqrt{\frac{n_2}{n_1}\left(\frac{n_1 + n_2}{n_H} - 1\right)}\right] \quad (3)$$

$$\mu_2 = \frac{\mu_H n_H}{n_1 + n_2}\left[1 + \sqrt{\frac{n_1}{n_2}\left(\frac{n_1 + n_2}{n_H} - 1\right)}\right] \quad (4)$$

for $n_1 => n_2$

To determine μ_1 and μ_2 we can greatly simplify the calculation by using two approximations justified by the experimental data. We assume $n_1 >> n_2$ and $n_H \approx n_1$ and obtain:

$$\mu_1 \approx \mu_H \quad (5) \quad \text{and} \quad \mu_2 \approx \mu_1 - \sqrt{\frac{\Delta n_H}{n_2}} \quad (6)$$

where we take $n_1 + n_2 - n_H = \Delta n_H$.[9]

Using n_2 from the Shubnikov-deHaas data and Δn_H from the Hall data we calculate μ_2 shown in Fig. 3c. Fig. 3c combined with Fig. 3a provides a complete map of the density dependence of the mobility of the 2D electron system within the transition regime from one-subband conduction to two-subband conduction, separately for each subband. In the following we will compare these results with theoretical calculations.

No calculation has been performed for a modulation doped GaAs-(AlGa)As heterojunction interface. However, the systems discussed by Mori and Ando, the Si-inversion layer[3] and the modulation doped GaAs-(AlGa)As superlattice[4] are closely related to this structure. Our experimental observations reproduce qualitatively all features of the density dependence of the mobility in the transition regime: Generally μ increases with increasing carrier concentration. This dependence is a result of improved screening of the ionized impurities which remain the major source of electron scattering[4]. At the onset of two-subband conduction μ_1 of the ground subband drops considerably due to the onset of intersubband scattering. Theoretically a mobility reduction by as much as a factor 3 is expected.[4] Our data show a reduction of 30%. The theoretical mobility variation at the transition point is discontinuous.[3,4] Though experimentally the transition occurs over a narrow density range it neverless is smooth. A slight density gradient can be responsible for the width.[10] However, a finite energetic width of the excited subband smears out the transition as well[3]. From a mobility of $\mu_2 \approx 20{,}000[\mathrm{cm}^2/\mathrm{Vsec}]$ we deduce a scattering time of $\tau \approx 7\mathrm{x}10^{-13}$sec and hence a level broadening of $\Delta E \approx 1$meV. In our 2D system with constant density of states 1meV corresponds to an electron density of $\Delta n \approx 3\mathrm{x}10^{10}[\mathrm{cm}^{-2}]$ in agreement with the finite width of the transition region. The shape of $\mu_1(n_s)$ reproduces well the results of calculations on intersubband scattering in Si inversion layers including finite subband width.[3] Most prominently the smearing out is not symmetric about the onset of occupation of the excited subband but appears almost exclusively on the high density side.

The mobility μ_2 of the excited subband is much lower than the ground subband mobility μ_1,[10] in qualitative agreement with the calculations[4]. The inferior mobility is a consequence of the smaller Fermi wave vector k_{F_2} compared to k_{F_1} (see Fig. 1). As a Coulomb potential scatters predominantly with small wave vector, ionized-impurity scattering has a stronger effect on a system having a smaller k_F. Again, the theoretical mobility ratio[4] μ_1/μ_2 exceeds the experimental data by factors 2 to 3. It is clear that a more careful theoretical treatment of mobilities in such structures is necessary.

In conclusion we report the observation of intersubband scattering in a 2D electron system. Our data provide the first direct evidence for the existence of this additional scattering channel. The density dependence of the mobilities in *both* subbands is determined. All features of the calculated density dependence of the mobilities are qualitatively reproduced. Quantitative discrepancies between theory and experiment remain.

Acknowledgement

We would like to thank A. Pinczuk, D. C. Tsui, S. J. Allen, B. Batlogg and V. Narayanamurti for discussions.

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[1] A good overview is found in the Proc. Intl. Conf. Electronic Properties of 2D System (I, II, III) published in: I: Surface Science *58* (1976), II: Surface Science *73* (1978) III: Surface Science *98* (1981).

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[9] Ideally $n_s = n_1 + n_2$ coincides with the extrapolated Hall density (see Fig. 2).

[10] Data taken at lower temperatures indicate that the finite temperature is not responsible for the spread.