X-conduction-electron transport in very thin AlAs quantum wells

S. Yamada
Nippon Telegraph and Telephone Corporation Basic Research Laboratories, 3-9-11, Midori-cho, Musashino-shi, Tokyo 180, Japan

K. Maezawa
Nippon Telegraph and Telephone Corporation LSI Laboratories, 3-1, Morinosato, Wakamiya, Atsugi-shi, Kanagawa 243-01, Japan

W. T. Yuen and R. A. Stradling
Department of Physics and Interdisciplinary Research Centre for Semiconductor Materials, Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW7 2BZ, United Kingdom
(Received 8 April 1993; revised manuscript received 16 August 1993)

Magnetotransport behavior of two-dimensional X-band electrons created in modulation-doped very thin (25–75 Å) AlAs quantum wells was studied. Effective-mass analysis based on temperature-dependent magnetoresistances clearly showed X_z-X_{xy} crossover at an AlAs thickness of about 45 Å. This value is much smaller than that in an AlAs/GaAs type-II superlattice (60 Å). Origins of this difference were discussed in terms of the effect of doping and degeneracy change and of the change of strain due to the structure difference.

Despite the importance of AlAs in potential optical and electronical applications, fundamental properties of this material have not yet been sufficiently clarified. Optical measurements such as photoluminescence and optical detected magnetic resonance, etc., however, have led to extensive reports about the Γ-X transition[1,2] and the X-band crossover[3–6] in AlAs/GaAs type-II superlattices (SL's). As a result, in undoped short-period AlAs/GaAs (thickness of 25 Å) SL's, the X-band crossover is thought to occur at a critical AlAs thickness of 60 Å.[5,6] On the other hand, two-dimensional magnetotransport studies in AlAs quantum wells have already been reported by several authors.[7,8] However, the AlAs thickness they have adopted was larger than 150 Å and hence only the occupation of X_{xy} electrons has been observed. That is, the problem of X-band crossover in modulation-doped systems has so far been an open question.

In this paper, we report the results of a magnetotransport approach to this problem, which is realized by using very thin modulation-doped AlAs layers. An advantage of this approach over the optical methods is to directly evaluate the effective masses of X-band conduction electrons. We can then detect the band crossover and unambiguously determine the critical condition. The bulk mobilities in AlAs, which might be too small to obtain a good quality Shubnikov–de Haas (SdH) effect, were fairly improved by modulation doping[9] into $Al_{0.45}Ga_{0.55}As$ barriers. This should enable us to observe good oscillations and thus determine the effective masses of two kinds of X-band electrons. In fact, we were able to observe good SdH oscillations in all samples having various AlAs thicknesses.

A schematic cross section of our $Al_{0.45}Ga_{0.55}As$/AlAs multiple-quantum-well (MQW) samples has been shown earlier.[10] The $Al_xGa_{1-x}As$ barrier was made thicker (250 Å) than in the usual type-II SL's in order to provide a sufficient doping layer (200 Å) and two spacer layers (25 Å×2). The AlAs well thickness d was either 25, 35, 45, or 75 Å. To make accurate measurements, we made a standard Hall bar sample (250 μm long and 25 μm wide) by photolithography. The first and second rows in Table I summarize those structure parameters and the results of

TABLE I. Subband parameters estimated for X-band two-dimensional electrons in four $Al_xGaAs_{1-x}As$/AlAs MQW's. Note that $m_z^*/m_0=0.19$ and $m_{xy}^*/m_0=0.48$ were previously estimated as the band-edge values.

Sample No.	1	2		3		4
AlAs thickness (Å)	25	35		45		75
period	20	20		20		10
$n_{s,\text{Hall}}$ ($\times 10^{12}$/cm^2)	2.7	1.6		1.3		2.5
$\mu_{e,\text{Hall}}$ (cm^2/V sec)	140	380		620		3000
Subband	0th	a (1st)	b (0th)	a	b	0th
$n_{s,\text{SdH}}$ ($\times 10^{12}$/cm^2)	2.0	0.5	2.0	0.8	1.8	1.2$^{(\times 2)}$
m^*/m_0	0.28±0.02	0.24±0.02	0.25±0.02	0.28±0.02	0.56±0.04	0.50±0.05
ϵ_f (meV)	23.8	5.8	23.8	9.5	9.3	6.2
X-band nature	X_z	X_z	X_z	X_z	X_{xy}	X_{xy}

Hall measurements at 1.5 K under a low current (~1 μA) and a low magnetic field (~1500 G). The low-temperature resistance was measured with a current of less than 10 nA to avoid electron heating. The applied magnetic field was at the most 10 T. To analyze the temperature dependence of the complicated magnetoresistance oscillations arising from several subband occupation systems, we used a reverse Fourier-transform method, as established earlier.[11]

For samples 1 and 4, which have AlAs well thicknesses of 25 and 75 Å respectively, the diagonal magnetoresistance R_{xx} showed only a single period oscillation indicating occupation solely of the bottom subband. Figure 1 is a typical example of the temperature-dependent magnetoresistance in sample 1. As shown in Fig. 2, however, the fitting curves of the normalized amplitudes of the oscillations against temperature revealed very different behavior for the different well thicknesses. That is, the oscillation amplitude for the 75-Å sample decreases faster and corresponds to an electron effective mass of about $m^*/m_0 \sim 0.5$, whereas that for the 25-Å sample decreases more slowly and corresponds to a mass of about $m^*/m_0 \sim 0.28$. Since the transverse and longitudinal electron masses[12] in AlAs are widely accepted to be $m_t^*/m_0 = 0.19$ and $m_l^*/m_0 = 1.1$, and band-edge masses for X_z and X_{xy} become $m_z^*/m_0 = m_t^*/m_0 = 0.19$ and $m_{xy}^*/m_0 = (m_t^* m_l^*)^{1/2}/m_0 = 0.48$. Therefore, we can identify the natures of the occupied subbands in samples 1 and 4 as X_z-like and X_{xy}-like, respectively. In other words, the nature of the bottom subband clearly differs between samples 1 and 4, indicating that X-conduction-band changeover occurs at an AlAs thickness between 25 and 75 Å also in the modulation-doped case treated here.

In the magnetoresistance measurements for samples 2 and 3, we found two occupied subbands. An analysis procedure to estimate an electron effective mass for each subband is as follows. (i) Carry out the first (sample 2) or the second (sample 3) derivative of the diagonal magnetoresistance. (ii) Take the Fourier power spectrum for the derivatives. (iii) Separate (two) Fourier spectrum peaks and reverse Fourier transform them independently. (iv) For the reproduced oscillations corresponding to each Fourier peak, apply theoretical fitting to those temperature dependencies of the amplitudes. Final mass values are determined by averaging the fitting results for at least three different magnetic fields. Thus, in sample 2, the X_z-like nature for both of the two subbands was confirmed. Note here that the electron densities of the two subbands are determined from the larger Fourier peak and from the difference of the two Fourier peaks. The reason is that the magnetoresistance oscillation in this sample almost reveals a beating behavior (not shown). This result seems reasonable because the bottom subband is lower than that in sample 1 due to the wider AlAs well (35 Å). In contrast, coexistence of X_z-like and X_{xy}-like electrons was observed in sample 3 having a 45-Å-thick AlAs well. Figure 3 shows a diagonal magnetoresistance signal and its second derivative. The Fourier power spectrum for the second derivative (shown in the inset) shows clearly two peaks, a and b, both which are reproducible up to about 5 K. The fitting results (Fig. 4) show that the oscillation corresponding to peak a gives an effective mass of about 0.28, and that for peak b gives a mass of about 0.56. In Figs. 4(a) and 4(b), the calculated curves corresponding to mass values of 0.55 and 0.3 were also plotted, respectively. Comparison of the two curves in each plot shows that this fitting procedure can definitely distinguish between the two mass values.

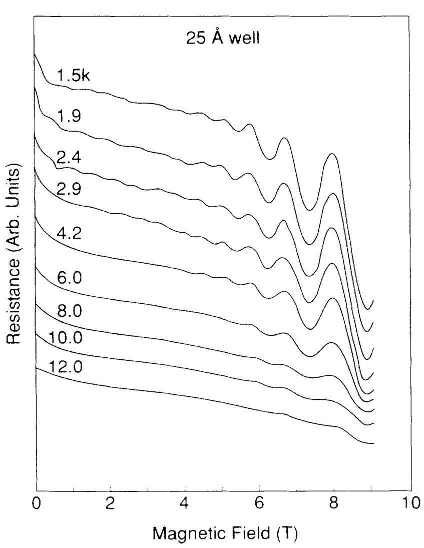

FIG. 1. Temperature dependence of diagonal magnetoresistance R_{xx} in sample 1 (AlAs well thickness $d = 25$ Å).

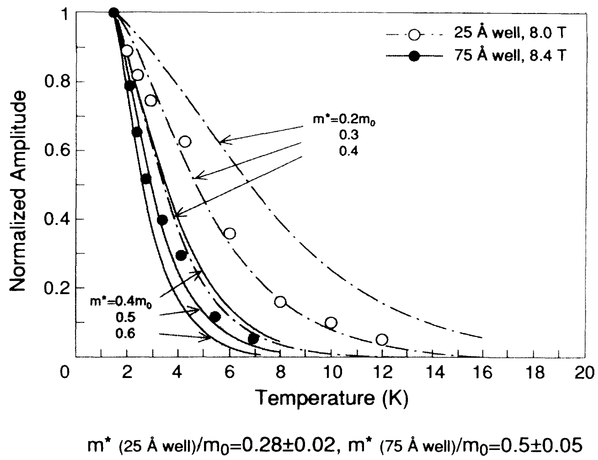

FIG. 2. Typical fitting results to calculations of the amplitude change against temperature for samples 1 and 4, which gives electron effective masses of about $m^*/m_0 = 0.28$ and 0.5, respectively.

Table I also summarizes various subband properties revealed in this analysis. Since two-dimensionality has been confirmed for all samples by tilting magnetic field (not shown), we can use the following well-known equation to derive Fermi energy ϵ_f for each subband:

$$\epsilon_f = \pi \hbar^2 n_s / m_b^* \ .$$

Here we used the band-edge mass values of $0.19m_0$ for X_z-like subbands and $0.48m_0$ for X_{xy}-like subbands. The most interesting result is that ϵ_f's of both subbands in

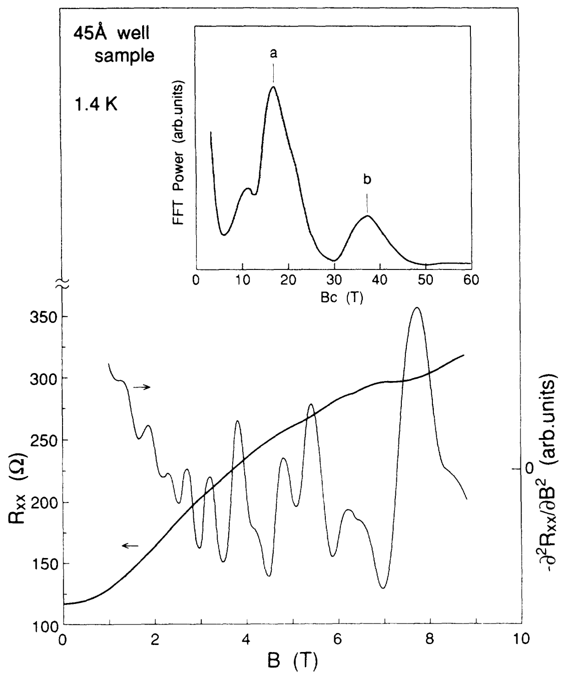

FIG. 3. Typical diagonal, magnetoresistance R_{xx} and its second derivative $\partial R_{xx}/\partial B$ for sample No. 3. Inset is a Fourier power spectra of the oscillation in the second derivative.

sample 3 accidentally have almost the same value. This directly indicates that the X_z-X_{xy} crossover occurs near the AlAs thickness of sample 3 (45 Å). The results from the other three samples are qualitatively consistent with that of sample 3, supporting the new picture of X-band changeover reported here.

Here, we comment on the n_s (sheet electron density) difference between the Hall and the SdH results especially in the samples 1–3. In such a case as having a single subband occupation and a high mobility, these two densities should be equal. In our samples, however, subband

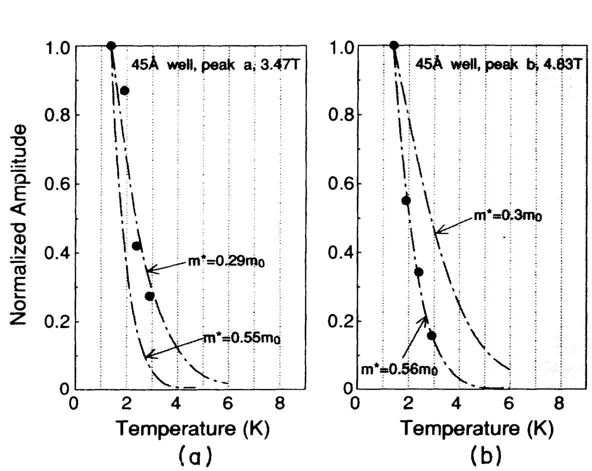

FIG. 4. Results of fitting of temperature dependences of amplitude for the two kinds of oscillations included in the magnetoresistance shown in Fig. 3, each of which should give the electron effective mass for each subband.

mobilities are relatively low and there may be a mobility difference between the occupied subbands. If the mobility of one subband is very low, the electron density of such a subband makes little contribution to the total electron density obtained in the Hall results. In addition, it is difficult to know the number of active AlAs layers[7,8] without doing a correct and careful measurement of the quantum Hall effect. Unfortunately, quantum Hall plateaus in our samples were not clear within the field and the temperature range we used here (≤ 10 T and ≥ 1.4 K, respectively). Since we assumed a full layer (10 or 20) activity in Hall measurements, the electron densities and the Hall mobilities in Table I are likely underestimated depending on the sample. Note further that $n_{\rm SdH}$ is about a half of the $n_{\rm Hall}$ in sample 4. This suggests that there is likely a change of degeneracy (from 1 to 2 without spin)[7,8] when the nature of the bottom subband electron changes from X_z-like to X_{xy}-like. Such origins as described above might be the cause of the difference between the results from the two methods. A complete description about this problem is at present an open question.

Here we briefly consider some possible origins of the difference between the critical thickness of the AlAs in AlAs/GaAs type-II SL's and that in modulation-doped $Al_xGa_{1-x}Al$/AlAs MQW's (this system). First, we assume that the effect of modulation doping upon the conduction-band potential profile is small, since the AlAs thicknesses studied here should be sufficiently thin. In other words, the potential form of these QW's approximates the rectangular shape for undoped GaAs/AlAs SL's. Then, a large stain-induced splitting of over 30 meV is necessary to explain the smaller critical thickness of AlAs, 45 Å, at which X-band changeover occurs. This splitting is about 50% greater than the values [23 meV (Refs. 5 and 6) or 19 meV (Ref. 10)] estimated by using the widely accepted values of shear deformation potential, elastic constants, and stress. The average Al content of our MQW's (~ 0.534) is somewhat larger than that in AlAs/GaAs type-II SL's (0.5). Moreover, biaxial strain from the GaAs substrate in the MQW samples applies to all epitaxial layers, whereas that in type-II SL's acts only on AlAs layers. It seems, however, impossible to attribute such a large strain-induced energy shift only to the material/structure difference. We therefore consider next the effect of doping upon the QW potential profile.

To evaluate this effect, we have carried out a self-consistent calculation of Schrödinger's and Poisson's equations under simplified conditions. The X-conduction-band discontinuity between $Al_{0.45}Ga_{0.55}As$/AlAs was assumed to be 150 meV and the electrons were assumed to occupy only the bottom subband. As a result for samples 1, 2, and 3, energy levels of X_z and X_{xy} electrons in AlAs wells, E_z and E_{xy}, are found to be almost equal to those in nondoped wells.[5,6] This means that the effect of doping is very small when AlAs thickness is smaller than 45 Å. In contrast, in sample 4, the ground X_z and X_{xy} levels were, respectively, found to be located at 33 and 47 meV (Ref. 10) (if we take the well bottom as zero), which are fairly higher than those in the nondoped case. Of course, we used here the standard m_t

and m_l values to determine the sublevels of X_{xy} and X_z. Actually, an envelope-function-type calculation[6] yielded 5 and 23 meV, respectively, for X_{xy} and X_z ground levels in the type-II SL with 75-Å-thick AlAs. The effects of doping are therefore twofold: One is to pull up both levels from the well bottom. The other is to decrease the difference between those two levels. In fact, the difference is 18 meV for the undoped well, and it is 14 meV for the doped well. If the same strain-induced splitting of 23 meV (Refs. 5 and 6) is assumed for both, the differences between the X_z and X_{xy} levels become 5 (=28−23) and 9 (=56−47) meV for undoped and doped wells, respectively. This implies that modulation doping shifts the X-band crossover point toward the direction of a thinner AlAs layer, although it is not enough to explain the total shift observed here (from 60 to 45 Å). Note here that the effect of degeneracy mentioned above is included implicitly in those self-consistent calculations. That is, an electron density which is about half of that from the Hall measurement was assumed. Also due to this effect, energy-level variation against the AlAs well thickness is likely not monotonic but abruptly changing at the crossover thickness in the modulation-doped case. The change of the crossover AlAs thickness may thus be attributed partly to the effect of doping and partly to the change of strain due to the structure/material change, although the details are not completely resolved.

In summary, we have studied transport behaviors in the two-dimensional X band in modulation-doped $Al_xGa_{1-x}As/AlAs$ multiple quantum wells when the AlAs thickness was varied from 25 to 75 Å. Effective-mass analysis based on low-temperature magnetoresistance measurements revealed that X-band crossover occurs at an AlAs thickness of about 45 Å. In other words, X_z electron occupation was first observed in AlAs QW's. The origins of this small critical thickness were discussed in terms of the effect of doping and the possible change of the strain itself.

We are indebted to Yuji Hasuike for growing samples by molecular-beam epitaxy and to Suzuko Ishizawa for Hall bar fabrication. We also thank Dr. Takashi Mizutani, Dr. Kazuo Hirata, and Dr. Yoshiji Horikoshi for their advice and continuing encouragement.

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