Large spontaneous spin splitting in gate-controlled two-dimensional electron gases at normal $In_{0.75}Ga_{0.25}As/In_{0.75}Al_{0.25}As$ heterojunctions

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(Received 3 July 2000; accepted for publication 12 February 2001)

Amounts of spontaneous spin splittings were estimated from low-temperature magnetoresistances in two-dimensional electron gases created at $In_{0.75}Ga_{0.25}As/In_{0.75}Al_{0.25}As$ heterojunctions under a gate bias. Typical sheet electron densities and mobilities in the raw wafers were $\sim 1.0\times 10^{12}/cm^2$ and $2-5\times 10^5\ cm^2/V\,s$ at 1.5 K, respectively. A maximum spin-orbit coupling constant α_{zero} of ~ 30 ($\times 10^{-12}$ eV m) was obtained for the van der Pauw sample. In gated Hall-bar samples, a decrease in the α_{zero} value with decreasing gate voltage (V_g) was first confirmed in a normal heterojunction. The main origin for such a large α_{zero}, which is a few times larger than any previously reported, was found to be a structure-dependent so-called interface contribution in the Rashba term. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1362356]

I. INTRODUCTION

Spontaneous or zero-field spin splitting in compound semiconductors has been believed to have a two-fold origin: One is the bulk inversion asymmetry that typically appears in a zinc-blende structure, and is proportional to k^3, where k is the wave number of the electron. The other is the structure inversion asymmetry (SIA). In this case, the splitting appears when k crosses the electric field due to the SIA. The extent of the splitting is proportional to k and, hence, the dispersion relation of a spin-splitting electron is represented as $h^2k^2/2(2\pi)^2m^* \pm \alpha k$,[1] where α is a spin-orbit coupling constant. The dispersion gives a zero-field spin splitting of $2\alpha k_f$ at the Fermi level, which is referred as a Rashba term in contrast to the field-proportional Zeeman term. Pioneering works on two-dimensional electron gases (2DEGs) confined at the heterojunctions with a narrow-gap well (such as $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$, InAs/GaSb, etc.)[1,2] have confirmed that most plausible origin of the spin splitting at low fields is the latter mechanism. Recent works on the gated control of α_{zero} by Nitta *et al.*[3] and by Engels *et al.*[4] have generated renewed interest in this area. They have used inverted $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$[3] or inverted pseudomorphic $In_{0.77}Ga_{0.23}As/InP$[4] heterojunctions in their three-terminal devices. The spin-field effect transistor (spin-FET)[5] seems to be becoming a realistic target and is thus generating a lot of interest. However, the Rashba term itself is still a controversial problem in terms of both experiment and theory: For example, in InAs/AlSb heterointerfaces, it has not been possible to obtain the gated control of α_{zero} at high 2DEG densities[6] and oscillation with beating was observed only when the longitudinal magnetoresistances (MRs) were measured between the voltage probes separated within a short (200 μm) distance.[7] Moreover, α_{zero} values give a rough spin-precession sensitivity in terms of V_g and those reported to date remain relatively small, e.g., $10-15\times 10^{-12}$ eV m even at 0.3–1.5 K. Therefore, in order to explore the intrinsic origin of spontaneous spin splitting and to allow a more plausible discussion of the future possibilities of the spin-FET, the creation of new alternative heterojunctions which have a larger spontaneous splitting as well as better electronic qualities is desirable. The electronic qualities, represented by the electron mean-free-path and/or the phase coherence length, seem to be closely related to the spin-dephasing length.[8]

We recently proposed and investigated a new heterojunction, $In_xGa_{1-x}As/In_yAl_{1-y}As(x,y>0.6)$, that consists of two narrow-band gap materials.[9] In particular, the sample with $x=y=0.75$ could be a candidate for closely approaching operation as a spin-FET due to its narrow-band gap and high 2DEG mobility of up to $5\times 10^5\ cm^2/V\,s$ at low temperature. In addition, the heterojunction of the $x=y=0.75$ material was found to have very large spin-orbit coupling constants α_{zero} of $\sim 30(\times 10^{-12}$ eV m) at 1.5 K.[10] In this work, we report in detail on the results of obtaining such large zero-field spin splittings and on the unique gate-dependent features that were first obtained in normal heterojunctions. The possible origins of this large α_{zero} are discussed in view of the relation between the well structure and the interface contribution of the Rashba term. This contribution is related to the asymmetry in the penetration of the 2DEG wave function to barriers on either side and is also related to the potential jump at the interfaces.

II. SAMPLE PREPARATION

The layered structure of our heterojunction, which was grown by molecular beam epitaxy, is described elsewhere.[9] The typical sequence of layers, from the top, is as follows: 15 nm $In_xGa_{1-x}As$ cap, 40 nm Si-doped $In_yAl_{1-y}As$, 20 nm $In_yAl_{1-y}As$ spacer, 30 nm (or 10 nm) $In_xGa_{1-x}As$ channel, $In_yAl_{1-y}As$ step-graded buffer, GaAs buffer, and semi-insulating (001) GaAs substrate. MR measurement was carried out on van der Pauw ($5\times 5\ mm^2$) and Hall-bar ($500\times 40\ \mu m^2$) samples. The Hall-bar sample had a Ti/Au front-gate

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TABLE I. List of mobility (μ_e) and sheet electron density (n_s) as measured for three van der Pauw samples.

Sample x/y	Hall measurement (4.2 K)		SdH measurement (1.5 K)	
	$\mu_{e,\mathrm{Hall}}(\times 10^4 \mathrm{cm^2/V\,s})$	$n_{s,\mathrm{Hall}}(\times 10^{11}/\mathrm{cm^2})$	$n_{s,\mathrm{SdH},sp}(\times 10^{11}/\mathrm{cm^2})$[a]	$n_{s,\mathrm{SdH},dg}(\times 10^{11}/\mathrm{cm^2})$[b]
0.75/0.75	39.7	10.0	5.8	11.6
0.75/0.66	~23	~12	7.1	14.1
0.5/0.5	9.5	12.0	···	9.7

[a]Means the value obtained on the assumption of spin splitting.
[b]Means the value obtained on the assumption of spin degeneracy. So that, $n_{s,\mathrm{SdH},dg}=2\times n_{s,\mathrm{SdH},sp}$.

attached via a ~60 nm SiO_2 insulator. A result from standard Hall measurements of the $x=y=0.75$ van der Pauw sample is given in Table I, with the results for $x=0.75/y=0.66$ and $x=y=0.5$ samples listed for comparison. As is suggested by the table, relieving the interface from strain and/or decreasing the alloy scattering by increasing the In content certainly enhances the low temperature 2DEG mobilities. For all $x=y=0.75$ wafers, the sheet electron density, $n_{s,\mathrm{Hall}}$, and mobility, μ_e, at 4.2 K were found to be $\sim 1\times 10^{12}/\mathrm{cm^2}$ and $2-5\times 10^5\,\mathrm{cm^2/V\,s}$, respectively. In order to estimate the spin-orbit coupling constant α_{zero}, low-temperature (1.5 K) Shubnikov de-Haas (SdH) oscillations were measured with and without gate bias in ac lock-in technique. The fast Fourier transformation (FFT) and nodes Landau plot[11] were used in analysis of the beats that appeared in the low-field region of the SdH oscillations.

III. RESULTS

Figure 1(a) shows B^{-1} plots of the first derivative (dR_{xx}/dB) of magnetoresistance (R_{xx}) for the $x=y=0.75$ (upper panel), $x=0.75/y=0.66$ (middle), and $x=y=0.5$ (lower) van der Pauw samples, i.e., the samples in Table I. The insets show the raw R_{xx} data. In the upper and middle panels, a beating pattern is clearly visible and its nodes are indicated by vertical arrows. This suggests that the 2DEG is occupying two subbands with slightly different electron densities. In contrast, one only finds simple oscillation with no beating pattern in the lower panel for the $x=y=0.5$ case. In Fig. 1(b), we show the results of FFT analysis of the dR_{xx}/dB oscillations in Fig. 1(a). Note here that the FFT analysis was carried out for those oscillations within 0.4 or 0.5–2 T, the low-field part of the oscillations. This limiting is crucial in excluding the contribution from the Zeeman term as is discussed later. In the case of $x=y=0.75$ (upper panel), the four major peaks labeled a, b, c, and d appear from the lower field. It is easy to presume on mathematical ground that the two strong peaks at around 10 T that have almost equal heights correspond to the two occupied subbands, the n_ss of which, $n_s(-)$ and $n_s(+)$, are beating with each other. Peaks a and d are then found to correspond to the difference and sum of these two components, i.e., $n_s(+)-n_s(-)$ and $n_s(+)+n_s(-)$, respectively. In the middle panel, for $x=0.75/y=0.66$, it is possible to identify similar peaks, except that the peak d has disappeared. In this case, peaks b and c are also relatively stronger than peak a. The result for the $x=y=0.5$ sample has, however, only a single major peak at about 15 T. This clearly corresponds to the fact that almost no beating oscillation in R_{xx} was observed in this case [lower panel of Fig. 1(a)].

If we assume that the two strong peaks mentioned above are the spin-split ones, we can derive the spin-orbit coupling constant α_{zero} from the separation of the FFT peaks or the beat node plots by using this equation[11]

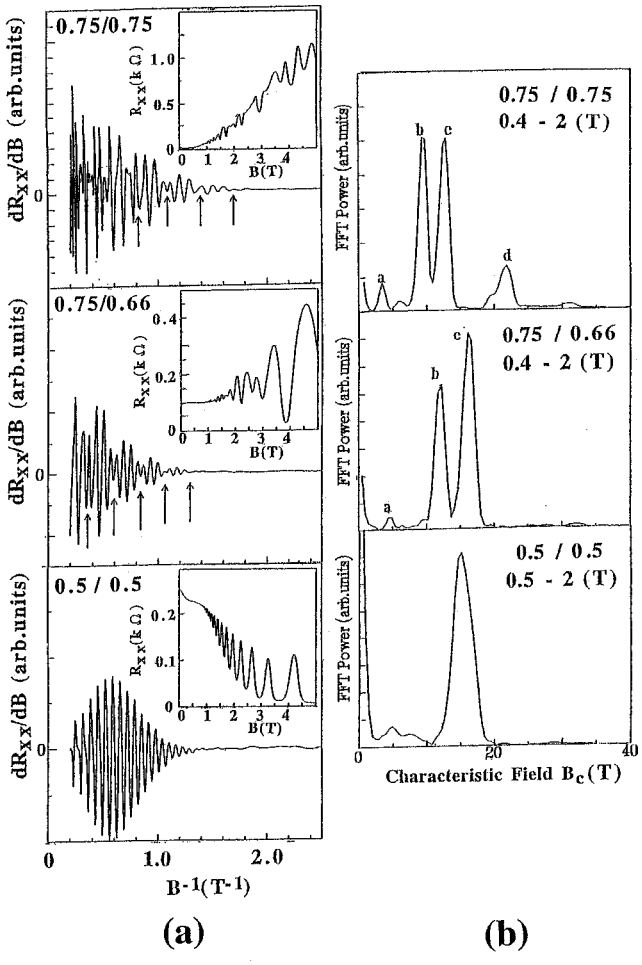

FIG. 1. (a) First derivatives of R_{xx} (dR_{xx}/dB) as a function of inverse magnetic field, B^{-1}, for $x=y=0.75$ (upper panel), $x=0.75/y=0.66$ (middle), and $x=y=0.5$ (lower) heterojunction samples. R_{xx} values (insets) were measured at 1.5 K. In the upper and middle panels, vertical arrows identify the beat nodes of the magnetic field. (b) Results of FFT analysis of the data given in (a). Upper panel: $x=y=0.75$ sample, middle: $x=0.75/y=0.66$ sample, lower: $x=y=0.5$ sample. Note here that only the dR_{xx}/dB data in the low field (0.4/0.5–2 T) range is analyzed.

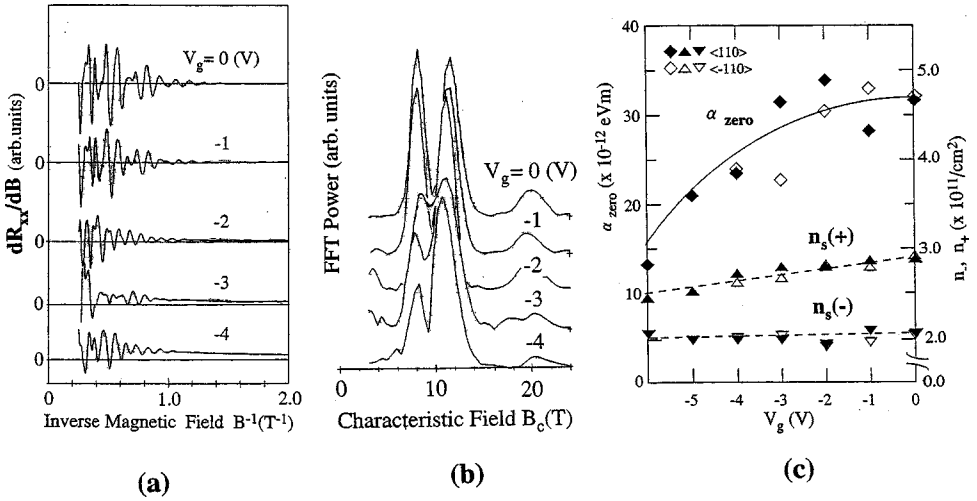

FIG. 2. (a) Gate-dependent dR_{xx}/dBs as functions of B^{-1} for $x=y=0.75$ gated Hall-bar samples with $\langle -110\rangle$ current direction. Beating oscillation is observed at all V_g values. (b) Results of FFT analysis of the data given in (a). At $V_g=-2$ and -4 V, the peak heights of the two main peaks are quite different, and the reason for this is not clear at present. (c) Gate dependences of sheet electron densities of the split subbands, $n_s(+)$ and $n_s(-)$, and spin orbit coupling constant, α_{zero}. Note here that α_{zero} for this sample reaches up to $\sim 30(\times 10^{-12}\,\mathrm{eV\,m})$ at $V_g=0$.

$$\alpha_{\mathrm{zero}}=(he/4\pi m^* k_f)(\Delta i/\Delta B^{-1}). \tag{1}$$

This procedure gives $\alpha_{\mathrm{zero}}=26.7$ and $26.8(\times 10^{-12}\,\mathrm{eV\,m})$ for the samples with $x=y=0.75$ and $x=0.75/y=0.66$, respectively. In addition, in the illuminated $x=y=0.75$ sample, $\alpha_{\mathrm{zero}}=29.2(\times 10^{-12}\,\mathrm{eV\,m})$ was obtained. Here, far-infrared absorption was also used to determine an m^*/m of ~ 0.041 for the $x=y=0.75$ and $x=0.75/y=0.66$ samples. Schapers *et al.*[11] have proposed another method of estimating $\alpha_{\mathrm{zero,total}}$ from the FFT result, although their method includes a contribution from Zeeman effect. The equation is as follows:

$$\alpha_{\mathrm{zero,total}}=(\Delta n h^2/4\pi^2 m^*) \quad \{(\pi/2)/(n-\Delta n)\}^{1/2}, \tag{2}$$

where $n=n_s(+)+n_s(-)$, $\Delta n=n_s(+)-n_s(-)$. From this equation, $\alpha_{\mathrm{zero,total}}=30.5$ and $32.3(\times 10^{-12}\,\mathrm{eV\,m})$ were obtained for the $x=y=0.75$ and $x=0.75/y=0.66$ samples, respectively. We thus note that the contribution of the Zeeman term makes up almost 10%–20% of the total in this estimation. This result justifies our adoption of a field range from 0.4 or 0.5 to 2 T in the FFT analysis. As discussed later, an independent g^* factor analysis also shows that the critical field strength in our samples, beyond which Zeeman term becomes dominant, is about 3.5 T. When the two $x=0.75$ samples with different y components are compared, the degree of interface strain[12] seems not to suppress α_{zero} at this stage. Although a simple comparison is difficult, the α_{zero} values obtained here represent a record for those obtained in various narrow-gap channel heterojunctions: For example, Luo *et al.*[1] have estimated a value of $\sim 9\times 10^{-12}\,\mathrm{eV\,m}$ for GaSb/InAs/GaSb quantum wells. Nitta *et al.*[3] obtained $\sim 10\times 10^{-12}\,\mathrm{eV\,m}$ for $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterojunctions. Engels *et al.*[4] have reported $\sim 15\times 10^{-12}\,\mathrm{eV\,m}$ for $In_{0.77}Ga_{0.23}As/InP$ heterojunctions. Our values are thus around 2–3 times larger than those that have been previously reported. The possible origins of our large α_{zero} values will also be discussed later in Sec. IV.

Figure 2 is a typical result for a gated-Hall bar sample. Figure 2(a) shows the first derivatives of the R_{xx} when the V_g changed from 0 to -4 V. Beating oscillations can be seen in all traces and are reproducible across the three pairs of voltage probes with different (100, 200, and 300 μm) distances. The corresponding FFT result is shown in Fig. 2(b). For the Hall bar sample experiments, Hall bars of two kinds, with current directions parallel to $\langle 110\rangle$ and $\langle -110\rangle$ were prepared. By applying the same procedure as described above to the FFT results shown in Fig. 2(b), dependences of α_{zero} on V_g were obtained for the two kinds of samples. As can be seen, $n_s(+)$ and $n_s(-)$ decrease linearly with negative V_g, while the α_{zero} values are initially almost constant ($\sim 30\times 10^{-12}\,\mathrm{eV\,m}$ also in this sample) or show a slight increase at small negative V_gs, and decrease rapidly with larger negative V_gs. This dependence is contrary to the case for an inverted heterojunction, but is acceptable if a heterojunction of a normal type is assumed. In this case, the decrease of V_g produces two contradictory effects with each other. As is suggested from Eq. (1), the decrease of n_s produced by a decrease in V_g results in an increase in α_{zero}. Simultaneously, the decrease in V_g decreases the vertical electric field strength in the well, and this produces a decrease of α_{zero}. Although the two effects compete, the dependence on V_g can be explained, if we assume the dominance of the n_s effect for negative small V_g and the dominance of the field effect at large negative value of V_g. The effect of illumination (a slight increase of α_{zero}) mentioned in the previous section seems to be consistent with this. The rate of change of α_{zero} against V_g is almost $-3\times 10^{-12}\,\mathrm{eV\,m/V}$ at $V_g=-4.0$ V. This value corresponds to a $\sim\pi$ phase change of spin precession in a 1 μm long sample. It has also been found that as long as the α_{zero} dependence on V_g, there seems to be no in-plane anisotropy in our Hall bar experiment, although we obtained an anisotropy of mobility of $\sim 30\%$ at low temperatures in this sample. If this result is considered along with the independence of the beating upon

the probe distance, we can exclude in-plane structural inhomogeneities as the origin of the beating oscillation.

IV. DISCUSSION

First, we discuss the physical identities of the FFT peaks shown in Fig. 1(b). When a beating pattern is observed in R_{xx}, there are several possible ways for the 2DEG to occupy *two* subbands. One is the case for an almost spin degenerated as often observed in standard GaAs/AlGaAs single heterojunctions under low magnetic fields. In such a case, the 2DEG occupation of the ground and first-excited subbands can sometimes produce such beating. Peaks b and c in the upper and middle panels in Fig. 1(b) would then correspond to the first-excited and ground subands, respectively. Another possibility is the lifting of the spin degeneracy, that is, the case of finite zero-field spin splitting. Spin-split dispersion would then be responsible: there are inner and outer parabola with opposite directions of spin. Peaks b and c would then correspond to the spin-down (up) and spin-up (down) subbands.

Let us quantitatively discuss $n_{s,\mathrm{total}}$s in terms of the results in Fig. 1(b). If we here assume that there is no spin splitting under a zero field, we can deduce $n_{s,\mathrm{total}}$s for the three samples by using the equation, $n_{s,\mathrm{SdH},dg}=\Sigma 2eB_{c,\mathrm{peak}}/h$, where $B_{c,\mathrm{peak}}$ is a characteristic field of the FFT peak. Estimated values are listed in Table I. If the lifting of spin degeneracy is assumed, the $n_{s,\mathrm{total}}$ values then have the values of $n_{s,\mathrm{SdH},sp}=\Sigma eB_{c,\mathrm{peak}}/h$ and these are also listed in Table I. Of course, $n_{s,\mathrm{SdH},dg}=2\times n_{s,\mathrm{SdH},sp}$. If we compare $n_{s,\mathrm{SdH},dg}$ with $n_{s,\mathrm{Hall}}$ in Table I, the former is larger than the latter for the samples with $x=y=0.75$ and $x=0.75/y=0.66$, but these are not acceptable. Therefore, $n_{s,\mathrm{total}}=n_{s,\mathrm{SdH},sp}$ is reasonable in the two samples, but it results in $n_{s,\mathrm{total}}<n_{s,\mathrm{Hall}}$. This implies that there is some parallel conduction. Indeed, in the raw plots of R_{xx} in the insets of Fig. 1(a), upper and middle panels, we can see some backgrounds which might suggest parallel conduction in those samples, that is, $n_{s,\mathrm{SdH}}<n_{s,\mathrm{Hall}}$. This coincidence furthermore excludes the assumption of spin degeneracy and FFT results in Fig. 1 thus support zero-field spin splitting, at least for the two $x=0.75$ samples. As for the $x=y=0.5$ sample, however, peaks at 5 and 15 T in the lower panel of Fig. 1(b), indicate occupation of the first-excited and ground subbands with very little zero-field spin splitting (suggested by the upper slight shoulder in the main peak at 15 T), although the $n_{s,\mathrm{total}}$ that arises from SdH oscillation still does not reach the $n_{s,\mathrm{Hall}}$. Estimation of the α_{zero} values described in the previous section should now be the most plausible. Although there exists a further possibility of magneto-intersubband scattering as an origin of the beating, this is very unlikely due to the relatively small 2DEG sheet electron densities in our samples.

Next, we discuss the origin of the large α_{zero} values obtained in this work. As was discussed recently by Schapers *et al.*[11] and Pfeffer *et al.*,[13] a so-called ''interface contribution'' may be included in the α_{zero} value itself. This contribution is related to the asymmetry of penetration of the electron-wave function to the barriers on either side and is likely to be dependent on the potential jump at the well/barrier interfaces rather than on the vertical electric field in the well (which could be varied by the gate voltage). In the Schapers *et al.*'s work, the contribution of interface penetration reaches almost 60% of the total value of α_{zero}. Pfeffer *et al.* claimed that the contribution of this term reaches 97% of the total Rashba term at most. Although a conclusive answer has not yet been obtained, those discussions in these earlier works suggest the possible major role of the same contribution in our samples.

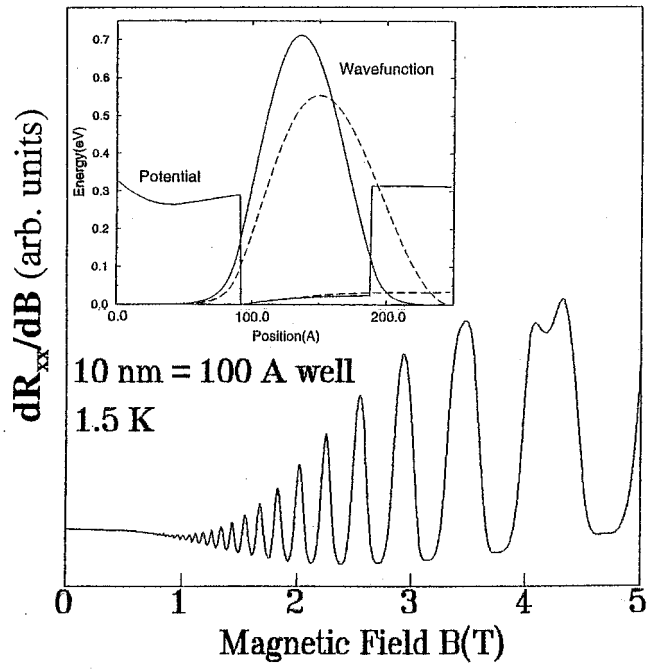

FIG. 3. Typical R_{xx} traces in a 10 nm well $x=y=0.75$ heterojunction, where no beating was observed. Inset is an example of self-consistent calculation (inset) for 10 nm (solid line) and 30 nm (dashed) well heterojunctions. In the inset, the left-hand side corresponds to the sample surface. The right-hand side barrier (bottom) of the 30 nm sample is beyond the horizontal range.

To analyze the extent of this contribution, we carried out MR measurements on a sample of a 10 nm $In_{0.75}Ga_{0.75}As$ well, for comparison. Figure 3 shows a typical MR result for the sample and the inset demonstrates the result of self-consistent calculations for samples with 30 and 10 nm wells. As seen in the figure, there is no beating in the signal for this sample, even at low fields. The major difference found in the results of these calculations is that, although the penetration of the wave function into the both side barriers is almost symmetrical in the 10 nm well sample, the penetration in the 30 nm well sample is fairly asymmetrical, in the sense that this case can almost be regarded as that of triangular potential confinement. In other words, the tails of the wave function symmetrically penetrate both $In_{0.75}Al_{0.25}As$ barriers in the 10 nm case, while only the upper tail penetrates the $In_{0.75}Al_{0.25}As$ barrier and the lower tail still exists within the $In_{0.75}Ga_{0.25}As$ well in the 30 nm sample. This big difference in the symmetry of penetration could explain the large α_{zero} values obtained for our samples. This possibility has not yet been widely examined or discussed, since a thicker well has

not been easy to fabricate due to the critical layer thickness, especially in pseudomorphic heterojunctions.

If the earlier discussion is true, the result in Fig. 3 suggests that the main origin of the large zero-field splitting in our case is an offset that originates in the interface contribution, as suggested by Pfeffer *et al.*[13] How can we explain the gate-voltage dependences seen in Fig. 2? We can point out that the gate-voltage-induced change in the asymmetry of penetration could be responsible for the gate-voltage-dependent variation in α_{zero}. There would be of course some contribution from gate-voltage-induced field variations, but the extent of this is not known at present. Another important point in relation to the earlier discussion is that the effect of strain has so far been only discussed in terms of holes.[13] When $y=0.66$, the conduction band discontinuity ($\sim$400 meV) is greater than in the $y=0.75$ sample ($\sim$280 meV). The asymmetry of penetration could therefore be smaller in the $y=0.66$ sample. Moreover, interface strain would probably suppress the spin-orbit coupling as predicted.[13] α_{zero} values are, however, almost the same for the two $x=0.75$ samples, as described in the former section. The reason for this result is still an open question at present, although the increase in the band discontinuity in the $y=0.66$ sample itself may contribute directly to the interface term as a potential ''jump'' enhancement.

Finally, we briefly discuss the contribution of the Zeeman term which is, to some extent, included in our estimates of α_{zero}. Analysis by the coincidence method[14] was carried out for 10 and 30 nm well samples and g^* values from -7 to -14 were obtained (not shown). From this result, the critical field strength above which the Zeeman term becomes dominant is estimated as 3.5 T. This clearly agrees with that the α_{zero} values estimated from Eq. (2) by using the FFT results below 2 T are only slightly greater than those obtained by using Eq. (1).

As Datta *et al.* pointed out in spin-FET proposal,[5] α_{zero} is a sensitivity factor of spin-precession angle against applied V_g. If we use the materials with large α_{zero} values as obtained in this study, the device length necessary to bring enough spin rotation becomes short. In fact, $\alpha_{\mathrm{zero}}\sim 30(\times 10^{-12}\,\mathrm{eV\,m})$ is assumed, the length L $(=2\pi^2\Delta\theta/h^2m^*\alpha_{\mathrm{zero}})$ to get a phase shift $\Delta\theta=\pi^3$ is only 0.11 μm. This degree of shortness is of practical importance, since the spin-dephasing length in the heterojunction is likely to be limited by the mean-free-path and/or the inelastic scattering length (in other words, the quality) of the 2DEGs.

V. SUMMARY

In summary, we have obtained very large α_{zero} values $<30(\times 10^{-12}\mathrm{eV\,m})$ from 2DEGs in $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}/\mathrm{In}_y\mathrm{Al}_{1-y}\mathrm{As}$ $(x=y=0.75)$ heterojunction structures. One possible reason for these findings is an interface contribution to the zero-field spin splitting, which might be enhanced in our unique heterostructures with a wider well and no strain. The gate-voltage dependence of α_{zero} was also confirmed in a unique manner for the normal type heterojunction adopted in this work and this can be explained by the change in the asymmetry of penetration of the wave function due to the gate voltage. The very large α_{zero} values observed in this work (corresponding to Fermi-level spin splittings of about 10 mV) might be an advantage in the operation of the spin-FETs of the future.

ACKNOWLEDGMENTS

This work is partly supported by a research grant on the Priority Area ''Spin-Controlled Semiconductor Nanostructures'' (No. 09244208) from the Ministry of Education, Science, Sports, and Culture in Japan. The authors also thank Dr. J. Nitta and Dr. M. Tomizawa of NTT Laboratories for frequent and fruitful discussions and for supplying self-consistent program, respectively.

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