Spin-related phenomena in nano-structure of semiconductors

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***Abstract*-The spin-related phenomena in semiconductor nano-structures were discussed for supporting the possible spin devices.**

I. INTRODUCTION

The spin-related phenomena in semiconductors have aroused extensive interests in the study of spin degree of freedom for its potential application in high-speed low-power electronic devices, such as spin-field effect transistor [1] and spin interference device [2]. The fundamental concept for such spin-based devices is spin splitting in semiconductor heterostructures.

The spin-orbit (SO) interaction in semiconductors originates from the Rashba term induced by structural inversion asymmetry (SIA) in heterostructures [3] and/or the Dresselhaus term induced by bulk inversion asymmetry (BIA) [4]. The Rashba SO coupling is of particular interest due to its potential applications in spin-field-effect transistor, as it can be controlled by an applied gate voltage [1][5]-[8]. Experimentally, zero-field spin-splitting effects can cause macroscopic effects like a beating pattern in Shubnikov-de-Hass oscillations, and/or mesoscopic effects such as antilocalization. The beating patterns in Shubnikov–de Haas oscillations and weak antilocalization (WAL) effects for HgTe/HgCdTe and InGaAs/InAlAs quantum wells, and $Al_xGa_{1-x}N$/GaN heterostructures have been investigated by means of magnetotransport measurements [9]-[10]. The zero-field spin splitting originated from the Rashba effect for all the quantum well and heterostructure samples were found. The principles of Rashba SO interaction in these nano-structure samples were elucidated.

II. GIANT ZERO-FIELD SPIN SPLITTING

The beating patterns in Shubnikov–de Haas oscillations for $HgTe/Hg_{0.3}Cd_{0.7}Te$ (001) quantum wells with electron densities of 2–3×10^{12} cm^{-2} have been investigated. Giant zero-field SO splitting energies up to 30 meV have been directly determined from the node positions as well as from the intersection of self-consistently calculated Landau levels (see Fig. 1). These values, which exceed the thermal broadening of Landau levels, k_BT, at room temperature, are in good agreement with Rashba SO splitting energies calculated by means of an 8×8 $\boldsymbol{k}\cdot\boldsymbol{p}$ Kane model [9]. The results make it possible to fabricate an electron spin device.

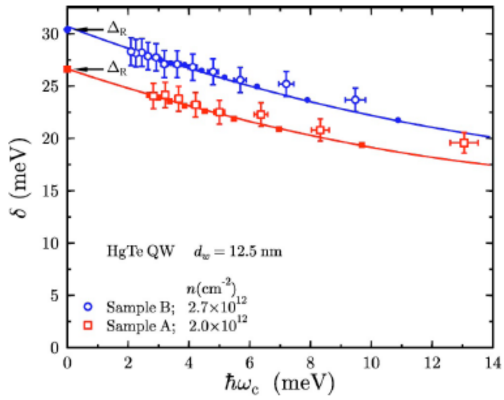

FIG. 1. Total experimental (open symbols) spin splitting energies and values calculated from the intersection of LL's (solid symbols) for samples A (no gate) and B (top gate) as a function of $\hbar\omega_c$. The zero-field spin splitting energies (solid symbols), Δ_R, are indicated by horizontal arrows. The lines are least-squares fits of the analysis of the self-consistently calculated LL's described in Ref. [9].

III. NONLINEAR RASHBA SPIN SPLITTING

The beating patterns in the Shubnikov–de Haas (SdH) oscillatory magnetoresistance have been investigated by means of magnetotransport measurements before and after illumination for a heavily Si δ-doped $In_{0.65}Ga_{0.35}As/In_{0.52}Al_{0.48}As$ single quantum well sample. After the illumination, the beating nodes in the SdH oscillatory magnetoresistance arose from spin splitting shift to lower magnetic field. It was investigated that the zero-field spin splitting energy and the spin-orbit (SO) coupling constant is weakened after the illumination. It was found experimentally that the intrinsic nonlinear Rashba spin splitting is the dominant mechanism of the zero-field spin splitting, verifying the nonlinear Rashba model proposed by Yang et. al [10] (see Fig. 2). The results can guide one to avoid overestimation of the spin-splitting for the spin-based devices.

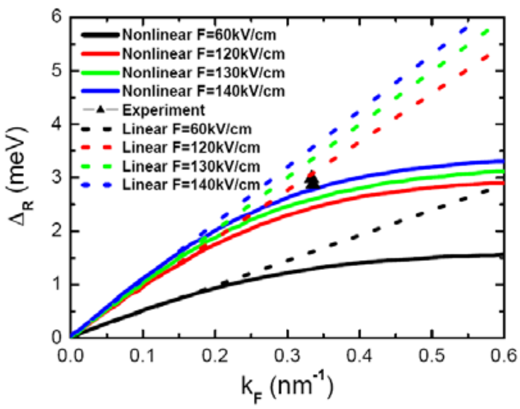

FIG. 2. Comparison of the linear model (dot lines) (Ref. [3]) with nonlinear model (solid lines) (Ref. [10]) for the zero-field spin splitting of lowest conduction subband of 15-nm-wide $In_{0.65}Ga_{0.35}As$/ $In_{0.52}Al_{0.48}As$ quantum well with various electric field. The experimental results (symbols) are also shown.

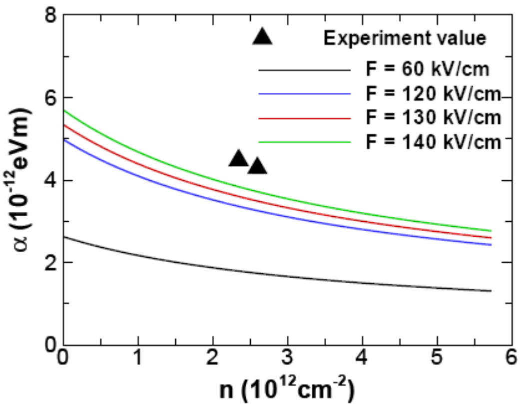

FIG. 3. Solid lines are the Rashba SO coupling constant of lowest conduction subband of 15-nm-wide $In_{0.65}Ga_{0.35}As$/ $In_{0.52}Al_{0.48}As$ quantum well with various electric field by nonlinear model (Ref. [10]). The experimental results (symbols) verify the nonlinear Rashba model since the Rashba SO coupling constant is increased due to the build in electric field increasing with the increase of electron concentration for linear Rashba model.

III. WEAK ANTILOCALIZATION EFFECT

The weak antilocalization (WAL) effects of the two-dimensional electron gas (2DEG) in $Al_xGa_{1-x}N/GaN$ heterostructure as well as beating patterns in the Shubnikov–de Haas (SdH) oscillatory magnetoresistance have been investigated before and after illumination [11],[12]. The zero-field spin splitting is decreased with the increase of electron concentration. The Rashba spin-orbit coupling constant deduced using the weak antilocalization analysis shows a rapid decrease with the increase of the measured electron concentration (see Fig. 4). Accordingly, the spin relaxation time is enhanced with the increase of electron concentration. The results suggest that two-dimensional gases (2DEGs) in $Al_xGa_{1-x}N/GaN$ heterostructures are potential candidates for gate-controlled spin precession utilizing the Rashba effect induced by SIA.

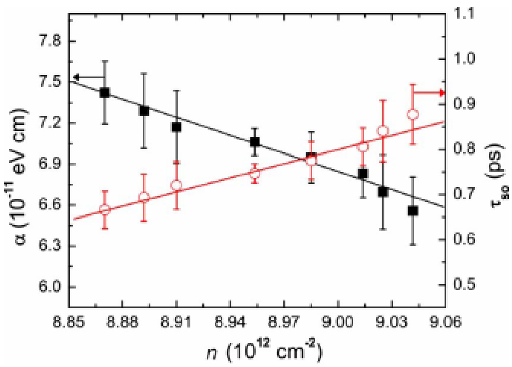

FIG. 4. Dependence of the Rashba SO coupling constant (solid symbols) and the SO scattering time (open symbols) on the electron concentration of the $Al_{0.22}Ga_{0.78}N/GaN$ 2DEG. (Ref. [12])

IV. SUBBAND ELECTRON EFFECTIVE g FACTOR

The electron g factor is another fundamental important parameter for spin-related devices [13][14]. We have investigated the spin splitting in the whole magnetic-field range in an $In_{0.8}Ga_{0.2}As/In_{0.53}Al_{0.47}As/In_{0.52}Al_{0.48}As$ graded heterostructure. A zero-field spin splitting of 3.82±0.09 meV and a magnetic-field-dependent effective g factor with g_0=13±0.93, and g_1=-4.51±0.14 were determined.

The spin-orbit coupling in a gate-controlled $In_{0.53}Ga_{0.47}As$/InP quantum well is investigated in the presence of a large Zeeman effect. A Fourier-transform fitting procedure has been developed to extract the zero-field spin-splitting Rashba parameter when Zeeman splitting is the same order of magnitude with Rashba splitting. The bare g factor value was found to be of the order of 3 from magnetotransport measurements in tilted magnetic fields. We find that both Zeeman splitting and Rashba splitting play important roles in determining the total spin splitting in $In_{0.53}Ga_{0.47}As$/InP heterostructures.

The large spin-splitting phenomena were also investigated in the inversion layer of p-type narrow gap semiconductors HgCdTe MIS structures. The possibilities of spin-related devices were discussed in the paper.

V. CONCLUSION

For all the above nano-structure quantum wells and heterostructures, the Rashba spin splitting is the dominant mechanism since the SIA along the growth direction is much prominent than the bulk inversion asymmetry (BIA) of the materials.

ACKNOWLEDGMENT

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