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Magnetotransport in Zener tunneling regime in a high-mobility two-dimensional hole gas

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In a high-mobility two-dimensional hole gas (2DHG) in C-doped (001) $GaAs/Al_{0.4}Ga_{0.6}As$ quantum wells, we observe sharp features in the differential magnetoresistance, which we interpret as the Zener-tunneling peak and valley associated with the commensuration transition of Landau orbits. Comparison of data with that in $GaAs/Al_{0.3}Ga_{0.7}As$ 2D electron gas suggests that the amplitude of Zener oscillations in a 2DHG is strongly damped. The data indicate the significant role of band structures in nonlinear transport in 2D electronic systems.

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Magnetotransport in $GaAs/Al_xGa_{1-x}As$ two-dimensional electron gas (2DEG) under a dc-current bias has recently revealed a number of interesting nonlinear phenomena, including the current-induced Zener oscillations[1] and zero-differential resistance states.[2] The Zener oscillations were first observed by Yang *et al.*[1] in a Hall bar sample of a modest high-mobility 2DEG (3×10^6 cm^2/Vs), when it is biased with a high dc current I_{dc}. In a magnetic field B (typically $B<1$ T), the magnetoresistance R_{xx} shows large amplitude, $1/B$ periodic oscillations, which can be understood as resulting from resonant Zener tunneling between Landau orbits tilted by the current-induced Hall field. It is further observed that such oscillations can persist up to a relatively high temperature $T\sim4$ K where Shubnikov–de Haas (SdH) oscillations are damped. In a different regime,[2] where the applied I_{dc} corresponds to a relatively small current density, a drastic drop in the differential resistance, or even a zero, was observed. Such findings have stimulated a series of theoretical[3] and experimental[4] investigations into the phenomena of nonlinear magnetoresistance of 2D electronic systems. In particular, Vavilov *et al.*[3] developed a theory of nonlinear response of electrons in a magnetic field. A significant result from Ref. 3 is that the amplitude of the oscillations can be associated with the carrier backscattering rates in a weak magnetic field, a parameter that is important for characterization of nonlinear electronic transport but hardly accessible in other experiments.

While the mechanism responsible for the above-mentioned phenomena in a 2DEG is in principle established,[1,3] it remains unclear whether similar phenomena could be observed in a different electronic system having distinct band structures. Specifically, we are interested in a high-mobility two-dimensional hole gas (2DHG), where spin-orbital coupling is significant.[5] Nonlinear transport phenomena in a 2DHG are particularly interesting, because spin-orbital interaction is thought to give rise to new effect, such as dc-current-induced spin polarization.[6] This Rapid Communication reports on our measurements on the dc-current-induced magnetotransport in high-mobility 2DHG in a C-doped (001) $GaAs/Al_xGa_{1-x}As$ quantum well (QW).[7–10] We observe the definitive differential magnetoresistance peak and valley associated with Zener tunneling of hole Landau orbits. Remarkably, comparing the results of 2DHG and that of 2DEG having similar scattering times, the oscillation amplitude in 2DHG is strongly damped, a fact that may be attributed to the hole carrier relaxation between spin-orbit-coupled heavy-hole subbands. Our finding underscores the roles that band structures play in the nonlinear transport in this regime.

Main results presented in this Rapid Communication were measured from samples A and B (Table I), which are the Hall bars processed with photolithography and wet etching on pieces cleaved from a molecular beam epitaxial wafer. The wafer has a 15-nm-wide $Al_{0.4}As_{0.6}As/GaAs/Al_{0.4}Ga_{0.6}As$ QW and a carbon doping layer 50 nm above the QW. Ohmic contacts to the 2DHG were made by diffusing Zn/In alloy on the Hall bar. Both samples have a hole density of $p\approx2\times10^{11}/cm^2$ and a mobility of $\mu\approx7\times10^5$ cm^2/Vs, determined from SdH measurements at $T=0.33$ K. We deduced the transport scattering time τ_{tr} from Drude relation $\tau_{tr}=m^*\mu/e$, where $m^*\approx0.4m_e$ is the hole effective mass [measured separately by microwave cyclotron resonance (CR) (Ref. 10)] and m_e is the free electron mass. The quantum scattering time τ_q was estimated from the onset of SdH, $\omega_C\tau_q\approx1$, where $\omega_C=eB/m^*$ is the hole cyclotron frequency. For comparison, the scattering times of a typical 2DEG sample used in Ref. 1, sample C, are also listed. It is worth emphasizing that the scattering times in A, B, and C are compatible, allowing us to examine the similarities and differences between Zener effects in two distinct electronic systems.

Before presenting our data in detail, it is useful to briefly summarize the findings in Ref. 1, where $1/B$ oscillations in differential magnetoresistance, r_{xx}, were observed when a dc-bias current I_{dc} is applied in a Hall bar sample. The position of the oscillation peaks was found to be $B_l\propto I_{dc}/wl$, where $l=1,2,3,\ldots$ is the order of peak and w is the width of the Hall bar. The effect, while rather spectacular, can be explained by a simple model[1] based on Zener tunneling of semiclassical electron orbits between N and $N+l$ Landau levels (LLs) (N is the LL index) in a Hall field E_y in which process an energy selection rule, i.e., $2R_CeE_y=l\hbar\omega_C$, is essential. Here $2R_C$ is the orbital diameter, a length scale characterizing the hopping distance ΔY. It was experimentally

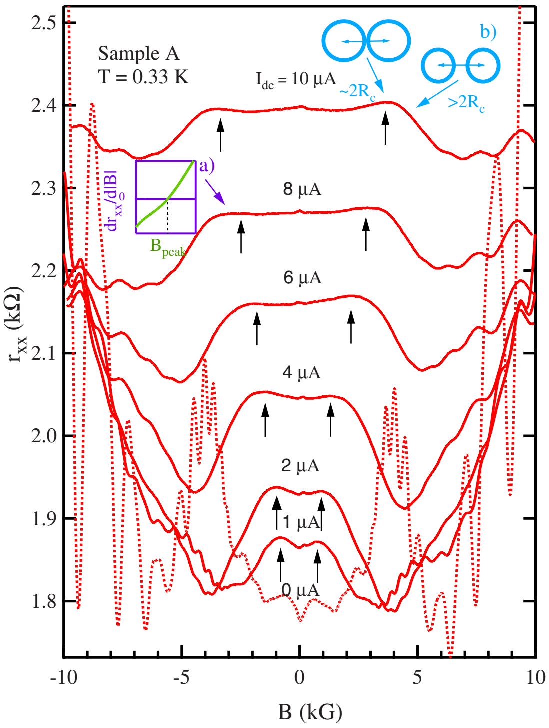

FIG. 1. (Color online) The differential magnetoresistance under $I_{dc}=0,1,2,4,6,8,10$ μA for the 50 μm Hall bar sample (sample A) at a temperature of 0.33K. A peak (up arrows) arises and shifts to higher magnetic field with the increase in I_{dc}. Inset (a) shows the point $dr_{xx}/dB=0$ that defines the peak; inset (b) is the illustration of Zener tunneling mechanism. Dot trace is the magnetoresistance under $I_{dc}=0$.

found that $\Delta Y=\gamma R_C$, where $\gamma\approx 2$. High amplitude (comparing to SdH) oscillations were observed up to $l=4$ in the samples of 3×10^6 cm^2/Vs mobility and, subsequently, to $l>10$ in very-high mobility ($\mu\approx 10^7$ cm^2/Vs) 2DEG in GaAs.[1,4] The oscillations can be viewed as, in effect, a series of geometrical resonance in a homogeneous 2DEG resulting from commensuration of orbit size with a periodic modulation of scattering rates.[1,3]

Our experiments on 2DHG were carried out by applying the differential resistance measurement technique described in Ref. 1, with samples immersed in the coolant (base temperature at 300 mK) of a top-loading Oxford helium3 refrigerator and the magnetic field B applied perpendicular to 2DHG plane. A calibrated thermometer placed in the vicinity of the sample was used to measure the coolant temperature.

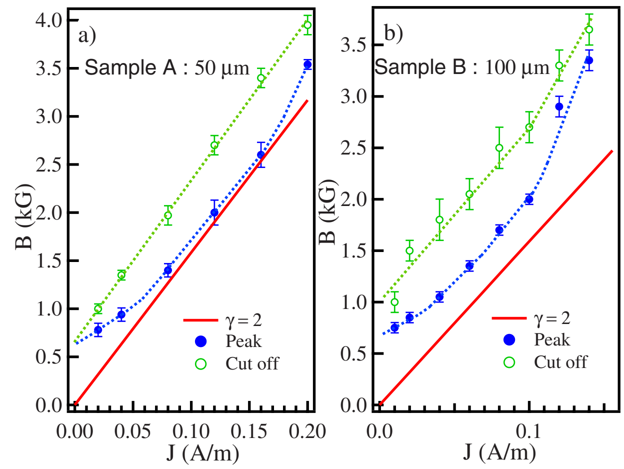

FIG. 2. (Color online) Experimental peak positions (solid dots) and the cutoff positions (open circles) are shown for (a) 50 μm (sample A) and (b) 100 μm (sample B) Hall bars. Solid lines are the theoretical results with $\gamma=2$; dot lines are guides for the eyes only.

A constant dc-current bias I_{dc} as well as a ac-modulation current, $I_{ac}=100$ nA with a frequency $f=17$ Hz, were fed through the sample, and the differential resistance, $r_{xx}=(\partial V/\partial I)_{I_{dc}}=v_{ac}/i_{ac}$, was then recorded by lock-in amplifiers at the modulation frequency.

Figure 1 shows, respectively, the r_{xx} traces for sample A under $I_{dc}=0,1,2,4,6,8,10$ μA. At $I_{dc}=0$, where standard magnetoresistance was observed, SdH shows sharp beating patterns, indicating the existence of two subbands. Fast Fourier transform analysis on SdH (Ref. 10) in the magnetic field range $B<3$ T yields the hole densities $p_+=1.0\times 10^{11}/\text{cm}^2$ ($p_-=1.1\times 10^{11}/\text{cm}^2$), respectively, for spin-up (spin-down) heavy-hole subband. There is about a 10% difference between them and the energy splitting is about 1.5 K, which is quite small and not enough to separate the two subbands, considering the Landau level broadening $\Gamma\approx 1.2$ K obtained from CR measurement.[10] However, SdH beats can still be resolved due to the resonance between two sets of Landau levels in a magnetic field sweep.[11]

We now focus on the data in the dc-bias regime, where we observe characteristic signatures of Zener tunneling previously observed in 2DEG. SdH oscillation diminishes and finally disappears presumably due to carrier heating effect of large I_{dc} current, and in the range $B<5$ kG, the r_{xx} is dominated by dc-induced features. Two features in the Fig. 1

TABLE I.

Sample	Width (μm)	Structure	Density ($10^{11}/\text{cm}^2$)	Mobility (10^5 cm^2/Vs)	Transport scattering time τ_{tr} (ps)	Quantum scattering time τ_q (ps)
A	50	15 nm C-(001) p-type $Al_{0.4}Ga_{0.6}As/GaAs/Al_{0.4}Ga_{0.6}As$ [a]	2.06	7	160	12
B	100	15 nm C-(001) p-type $Al_{0.4}Ga_{0.6}As/GaAs/Al_{0.4}Ga_{0.6}As$ [a]	2.08	5	114	14
C	50	Si-(001) n-type $GaAs/Al_{0.3}Ga_{0.7}As$ [b]	2	30	115	10

[a]Reference 10.
[b]Reference 1.

should be highlighted: (1) a broad peak in r_{xx}, which presents symmetrically on either magnetic field directions and which shifts to high B as the I_{dc} increases; and (2), a sharp drop in r_{xx} for each trace beyond a critical magnetic field. These two features correspond, respectively, to the maximum transition probability of Landau transitions and the cutoff of transitions taking place sequentially in increasing B, as depicted by the schematics in inset (b). Similar peaks were observed in the r_{xx} traces of the 100 μm Hall bar (sample B).

It is worthwhile to examine these features quantitatively as a function of the dc-bias current I_{dc}. For this purpose, we determine the B position of (1) by the derivative $dr_{xx}/dB=0$ (solid dots) and that of (2) by the maximum curvature of r_{xx}, e.g., $\mathrm{Max}|d^2r_{xx}/dB^2|$ (open circles). These data are plotted against the current density $J=I_{dc}/w$ in Figs. 2(a) and 2(b), respectively, for samples A and B. The fact that the peak positions are close to the $\gamma=2$ lines indicates that, indeed, these features are resulting from the Zener tunneling effect of 2D holes. As we will discuss in the text, due to spin-orbital coupling, the peaks may be smeared out by intersubband scattering. Other factors for consideration include the inhomogeneous current distribution across the Hall bar, especially in increasing J.

Figure 3 shows the temperature dependence of differential magnetoresistance of sample A at $I_{dc}=5\mu$A. In Fig. 3(a), the Zener peak disappears gradually as temperature goes up and can persist up to about 1.5K. We note that for 2DEG such temperature is about 4 K.[1] The different temperature dependence can be partly account for by the fact that the Fermi energy in 2DEG sample in Ref. 1 is about 80 K and that for sample A it is about 15 K. The slope of the differential magnetoresistance, i.e., dr_{xx}/dB, near the cutoff is drawn in Fig. 3(b). In fact, above 0.7 K the slope drops linearly as the temperature goes up. We have also measured the temperature dependence of $B=0$ resistance, shown in the Fig. 3(b), which indicates a T-linear dependence between $T=0.3$ and 1.5 K.

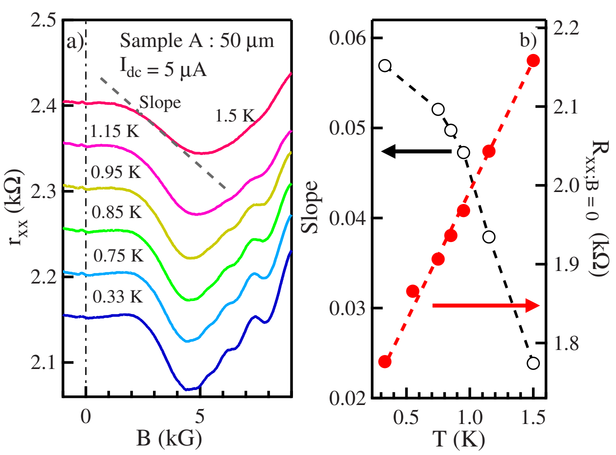

FIG. 3. (Color online) (a) The differential magnetoresistance traces are shown for 50 μm Hall bar (sample A) under $I_{dc}=5$ μA at 0.33, 0.75, 0.85, 0.95, 1.15, and 1.5 K, respectively. For clarity, the traces are vertically shifted consecutively by 0.5 kΩ. Dash line illustrates the slope. (b) Solid dots are zero-field temperature-dependent resistance data without applying I_{dc}; open circles are the slope for different temperatures in (a).

Such data appear to confirm that phonon scattering dominates scattering in this temperature range in our 2DHG for $B=0$, similar to that observed in GaAs 2DEG.[12]

To further examine the Zener effect in a 2DHG, we have measured the differential magnetoresistance in a gated Hall bar. A Ni/Cr metallic gate was fabricated on the surface of the Hall bar, which allowed us to increase the 2DHG density up to $\sim 4\times 10^{11}/\mathrm{cm}^2$. In the inset, a mobility vs hole density plot is shown. A somewhat puzzling result is that above approximately $p\approx 2.5\times 10^{11}/\mathrm{cm}^2$, the mobility drops roughly linearly with the carrier density. Notice that our QW is asymmetric due to one-side doping; increasing 2DHG density by the gate potential in effect enhances asymmetry and thereby increasing the Rashba spin splitting. The other factor for consideration is the interface scattering (including both the $Al_{0.4}Ga_{0.6}As$ barrier alloying scattering and the interface roughness scattering), which becomes important as the carrier wave function being shifted toward the barrier. We note that similar mobility vs density behavior has been reported for a gated 15 nm QW and was attributed to the intersubband scattering involving light hole subband in increasing density.[9]

Perhaps the more puzzling observation is that in increasing hole density, the Zener tunneling features disappears. Figure 4 shows the r_{xx} traces measured at $T=0.33$ K with $I_{dc}=1,2,4,6,8,10$ μA for a hole density $p=2.63\times 10^{11}/\mathrm{cm}^2$. Remarkably, the traces do not show any evidence of Zener effect. On the other hand, the $I_{dc}=0$ data show strong positive magnetoresistance, which indicates that multiband scattering dominates the transport in this regime.[7] All together, the data demonstrate that the smearing of Zener features happens concomitantly with the positive magnetoresistance, indicating the involvement of intersubband scattering.

In summary, we have observed the magnetoresistance features in a high-mobility GaAs 2DHG that are consistent with the Zener tunneling mechanism under a dc-bias current.

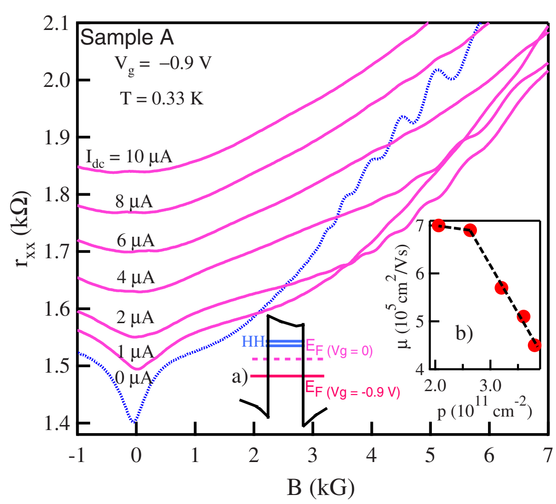

FIG. 4. (Color online) Differential magnetoresistance observed in a gated 2DHG sample is shown. Strong positive magnetoresistance is observed where there is no evidence for Zener tunneling peaks and valley. The inset shows the mobility as a function of carrier density in the gated Hall bar.

However, in stark contrast to the Zener effect observed in a GaAs 2DEG, such effect is strongly damped in 2DHG. In this study the samples A, B, and C have comparable scattering parameters. This fact indicates that the scattering times τ_{tr} and τ_q are not the only parameters characterizing the transport in Zener oscillation regime.

Presently we do not have a concrete explanation for the observed discrepancy in Zener amplitude between the 2DHG and the 2DEG. Several factors can be considered, however, which may have certain influence on the Zener effect. First, weakness of Zener tunneling in 2DHG may be due to damping via the Dingle factor. The stronger damping in 2DHG comes from its larger effective mass thus smaller Landau level spacing. Second, the valence band structure in a GaAs QW is known to be complex.[5] In the simplest case where only the spin-up and spin-down heavy-holes are occupied, in a strong bias current, disorder may contribute to scattering between spin-splitting subbands, thus broadening Landau levels. Moreover, with increasing hole density the effective mass of p_+ and that of p_- acquire different values; the Zener peaks should be further smearing out. Finally, the amplitude of oscillations in dc field is determined by the backscattering rate,[3] and this rate may be significantly different in various systems. Another reason why the dc oscillations are weak in 2DHS may be related to the quantum scattering rate without inhomogeneous broadening, i.e., even if SdH oscillations give comparable Dingle factor, suppression of Zener oscillations is determined by the Dingle factor without inhomogeneous broadening.

In conclusion, we have studied the Zener tunneling effect in a high-mobility 2D hole gas. The data are remarkably consistent with a simple model of commensuration transition of Landau orbits in a Hall field. On the other hand, quantitative differences between the amplitude of the Zener oscillations in 2DEG and 2DHG indicate that the usual transport scattering time and the Dingle factor cannot adequately describe nonlinear resistance in this regime. A quantum Dingle factor without inhomogeneous broadening is suggested to be responsible for such observations. A satisfactory understanding of nonlinear transport in 2DHG requires theories explicitly dealing with such phenomenon in spin-orbit coupled systems.

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