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We report on magnetotransport properties of a MgZnO/ZnO heterostructure subjected to weak direct currents. We find that in the regime of overlapping Landau levels, the differential resistivity acquires a quantum correction proportional to both the square of the current and the Dingle factor. The analysis shows that the correction to the differential resistivity is dominated by a current-induced modification of the electron distribution function and allows us to access both quantum and inelastic scattering rates.

Nonlinear magnetotransport in high Landau levels of two-dimensional electron systems (2DESs) offers a unique approach to obtain information on both electron-impurity and electron-electron scattering. For example, at high direct currents the differential resistance exhibits Hall field-induced resistance oscillations (HIRO) [1–11] which originate from electron (or hole [10]) backscattering off impurities leading to transitions between Landau levels. Since such transitions are accompanied by a displacement of the electron guiding center by a cyclotron diameter $2R_c$, applied current density $j$ translates to an energy scale $ej \rho_H/(2R_c)$, where $\rho_H$ is the Hall resistivity. HIRO then result from the commensurability between this energy and the inter-Landau level spacing $\hbar\omega_c$, where $\omega_c$ is the cyclotron frequency of a charge carrier. In overlapping Landau levels, the corresponding correction to the differential resistance $r$ is given by [12]

$$\frac{\delta r}{R_0} \approx \frac{16}{\pi} \frac{\tau}{\tau_n} \lambda^2 \cos 2\pi \epsilon_j, \quad \pi \epsilon_j \gg 1,$$

where $\epsilon_j = ej \rho_H/(2R_c)/\hbar\omega_c$, $R_0$ is the low-temperature, linear-response resistance at zero magnetic field ($B = 0$), $\tau$ is the disorder-limited transport scattering time, $\tau_n$ is the backscattering time, $\lambda = \exp(-\pi/\omega_c\tau_n)$ is the Dingle factor, and $\tau_n$ is the quantum lifetime.

The disorder in a 2DES can often be conveniently separated into a short-range (e.g., background impurities) and a long-range (e.g., remote ionized donors) component, characterized by “sharp” and “smooth” scattering rates ($\tau_{sh}^{-1}$ and $\tau_{sm}^{-1}$), respectively. When $\tau \gg \tau_n$, as in conventional high-mobility modulation-doped 2DES, $\tau_{sh} \approx \tau$ and $\tau_{sm} \approx \tau_n$ with very high accuracy [12].

Therefore, the analysis of the HIRO amplitude using Eq. (1) can yield information on both sharp and smooth disorder components in a 2DES under study.

In the regime of weak electric fields, the differential resistance acquires a negative quantum correction which scales with $j^2$, as has been observed in GaAs heterostructures [3, 4, 6, 8, 13–19]. In contrast to Eq. (1), this current-induced correction originates both from the low $\epsilon_j$ counterpart of Eq. (1) [12] (displacement mechanism) and from the oscillatory modification of the energy distribution function (inelastic mechanism) [20]. More specifically, in overlapping Landau levels, $\delta r$ can be written as [12]

$$\frac{\delta r}{R_0} \approx -\alpha \epsilon_j^2, \quad \pi \epsilon_j \ll \min\{1, (2\tau/\tau_n)^{1/2}\},$$

where

$$\alpha = \alpha_0 \lambda^2, \quad \alpha_0 = 12\pi^2 \left(\frac{3\tau}{16\tau_{\tau}} + \frac{\tau_n}{\tau}\right).$$

Here, $\tau_{\tau}^{-1}$ entering the first (displacement) term can be expressed as $\tau_{\tau}^{-1} = 3\tau_{0}^{-1} - 4\tau_{1}^{-1} + \tau_{2}^{-1}$, where $\tau_{n}^{-1}$ represents $n$-th angular harmonic of the rate of scattering on angle $\theta$, $\tau_{\theta}^{-1} = \sum_{n} \tau_{n}^{-1} e^{i n \theta}$ [21]. This displacement term can never exceed $9/16$ (sharp-disorder limit). In contrast, the second (inelastic) term in Eq. (3), given by $\tau_{\tau}/\tau \sim \hbar E_F / (\tau/k_B T)^2$ ($E_F$ is the Fermi energy, $\tau_{\tau}$ is the inelastic relaxation time), can be significantly larger than unity, especially in high density and low mobility 2DESs [8, 13–19]. In such systems, nonlinear transport at small $j$ offers a convenient way to obtain $\tau_{\tau}$ and thus access the strength of electron-electron interactions in the 2DES under study.

In this paper the capability of nonlinear transport to reveal information about scattering sources is exploited on a Mg$_{x}$Zn$_{1-x}$O/ZnO heterostructure [11, 22–27]. We find that the correction to the differential resistivity can be well described by Eq. (2). The analysis of the curvature $\alpha$ reveals that the observed nonlinear response is governed by the current-induced modification of the electron distribution function, consistent with the theoretical estimates. From the Dingle analysis we obtain $\tau_n \approx 2$ ps, in good agreement with the values found from recent measurements of Shubnikov-de Haas [24], microwave-induced [27], and Hall field-induced [11] resistance oscillations, confirming the applicability of Eqs. (2), (3).
importantly, our experiments allow us to estimate the inelastic relaxation time $\tau_{\text{in}} \approx 40$ ps, which could not be accessed in previous studies [11, 24, 27]. While similar approach has been previously employed to study inelastic relaxation in GaAs/AlGaAs quantum wells, a much lower mobility and higher density of our MgZnO/ZnO heterostructure suggest its potential applicability to a diverse variety of 2DESs.

Our sample was fabricated from a Mg$_x$Zn$_{1-x}$O/ZnO heterostructure grown using liquid ozone-based molecular beam epitaxy [26, 28]. A Hall bar of width of $\approx 0.09$ mm and distance between voltage probes of $\approx 0.8$ mm was defined by scratching the wafer with a tungsten needle [11]. Electrical contacts were made by soldering indium. At $T \approx 1.35$ K, our 2DES has density $n_e \approx 2.0 \times 10^{12}$ cm$^{-2}$ and mobility $\mu \approx 2.3 \times 10^4$ cm$^2$/Vs. The differential resistance $r$ was recorded using a standard four-terminal lock-in technique at a constant coolant temperature $T \approx 1.35$ K either while sweeping magnetic field $B$ at constant direct current $I$ or while sweeping $I$ at a constant $B$.

To facilitate the discussion of our results in the regime of weak currents, we first briefly summarize the main findings of related HIRO experiments. In Fig. 1(a) we present $r$ as a function of $B$ recorded at different $I$ from 0 (bottom curve) to 0.75 mA (top curve), in steps of 0.25 mA. The trace at $I = 0$ is rather featureless, showing only weak Shubnikov-de Haas oscillations at $B \geq 1$ T. The data at $I = 0.25$ mA and higher currents, however, reveal HIRO (cf. 1+, 2+) which spread over a wider $B$ range with increasing $I$. The positions of the HIRO maxima are well described by $B_N^+ \approx (m^* \sqrt{\pi n_e} / e^2) (j/N) \propto j/N$ [11], where $N = 1, 2, 3, ...$. However, in contrast to what one might expect, the increase in $I$ does not lead to observation of more oscillations. This is in line with the recent study [11] which found that $\tau_{\text{q}}$ decreases rapidly with $I$. Also, like Ref. 11, we observe that the zero-field differential resistance $r_0$ also increases with $I$, suggesting a decrease of $\tau$. Both observations are consistent with a scenario that Joule heating leads to elevated electron-temperature which, in turn, causes enhanced electron-electron and electron-phonon scattering [11]. Owing to this unintentional heating, our HIRO experiments never revealed more than three oscillations (regardless of $I$) which precluded extracting $\tau_{\text{q}}$ from a conventional Dingle analysis. Instead, we had to resort [11] to fitting experimental curves with the HIRO expression whose applicability, in contrast to Eq. (1), is not limited to $\pi \varepsilon_j \gg 1$ [12]:

$$\frac{\delta r}{r_0} = -\frac{2\pi}{\tau_{\text{sh}}} \lambda^2 \left( \zeta \left[ J_0^2(\zeta) \right]'' \right)' \quad (4)$$

Here, $J_0$ is the Bessel function and prime denotes a derivative with respect $\zeta = \pi \varepsilon_j$. Not surprisingly, the obtained $\tau_{\text{q}}$ value showed significant dependence on $I$, reflecting a sizable electron-electron scattering contribution

![Figure 1](image-url)

**Fig. 1.** (Color online) (a) $r(B)$ at different $I$ from 0 (bottom curve) to 0.75 mA (top curve), in steps of 0.25 mA. HIRO maxima are marked by 1+ and 2+. The curves are superimposed on a smooth, monotonically increasing background which closely mimics $r(I)$ at $B = 0$. An alternative way to study HIRO is to sweep $I$ while keeping $B$ fixed [3]. In Fig. 1(b) we present $r(I)$ at different $B$ from 1 to 2 T in steps of 0.25 T (solid lines) and at $B = 0$ (dashed line). At $B = 1$ T and higher, oscillations in $r$ with $I$ are superimposed on a smooth, monotonically increasing background which closely mimics $r(I)$ at $B = 0$. Concurrently, the oscillations move to higher $I$ with increasing $B$ while growing in amplitude. This increase originates from enhanced modulation of the density of states at higher $B$.

At the focus of the present work is a maximum centered at $I = 0$ which becomes more pronounced with increasing $B$, see Fig. 1(b). As we show below, this maximum appears due to Landau quantization, primarily, as a result of current-induced modification of the electron distribution function [12, 20]. We further illustrate how this feature can be used to obtain both quantum and
with increasing pressed and this suppression becomes more pronounced [11], and
m present in Fig. 2(b) above.

At small ǫ 2 ≪ 1, the differential resistance is suppressed and this suppression becomes more pronounced with increasing B. To examine this regime in detail, we present in Fig. 2(b) δR/RO(0) ≡ [R−R(0)]/RO(0) as a function of ǫj at different B from 0.6 (top) to 1.5 T (bottom), in steps of 0.1 T. While at B = 0.6 T the trace is virtually flat, the curvature rapidly increases with B. An example of a fit to the data at B = 1.5 T with Eq. (2) (dashed line) demonstrates excellent overlap with the experimental data at |ǫj| ≲ 0.2. As we show below, the applicability condition of Eq. (2) is well satisfied since (2πτ/τm)1/2 ≈ 0.5, which far exceeds our fitting range of |πǫj| ≲ 0.06.

We next fit our data at all other B and obtain the curvature α which is the only fitting parameter. Being guided by Eq. (3), we construct a Dingle plot, presented in Fig. 3, showing the reduced curvature α/12π 2 as a function of 1/B on a log-linear scale. At 1/B ≳ 0.7 T, the curvature exhibits exponential dependence from which we obtain τq ≈ 2.0 ps using Eq. (3). The deviation of the data from the exponential dependence at lower 1/B has been previously observed in experiments on GaAs quantum wells in the regime of separated Landau levels [8]. In our MgZnO/ZnO sample, the Landau levels start to separate at B ≈ 1.3 T, as estimated from ωeτq = π/2 [30, 31].

We now examine the intercept of the Dingle plot in Fig. 3 and extract the inelastic scattering time. We first recall that the first term in Eq. (3), representing the displacement contribution, has its maximal value of 3τ/16τe ≈ 9/16 (sharp disorder limit), a condition which was established in a recent HIRO study [11]. Since the intercept of the fit in Fig. 3 yields α0/12π 2 ≈ 11 ≫ 9/16, we conclude that the inelastic mechanism dominates the nonlinear response at small direct currents in our MgZnO/ZnO heterostructure. From this value, we then find τm ≈ 40 ps.

It is interesting to compare the obtained value of τm to the one expected from theoretical considerations [20, 32]. In the regime of our experiment [33], theory predicts

$$\tau_m \approx 0.82 \tau_{ee} , \quad \frac{h}{\tau_{ee}} \approx \frac{\pi k_B^2 T^2}{4 E_F} \ln \left( \frac{2v_F}{\alpha_B \omega_e \sqrt{\omega_e T}} \right) ,$$

where τ−1  ee is the electron-electron scattering rate for a test particle at the Fermi energy, v_F is the Fermi velocity,
and $a_B \approx 1.5$ nm is the Bohr radius. At $B = 0.7$ T, the logarithmic factor is about 5.9 and Eq. (5) yields $\tau_{in} \approx 140$ ps, a few times larger than the value obtained from our Dingle analysis.

Since we have limited our analysis to currents considerably smaller than those needed to induce noticeable change in $r$ at $B = 0$, we believe that any residual Joule heating is unlikely to be responsible for this discrepancy. On the other hand, Eqs. (2), (3) were derived assuming $\omega_c \tau \gg 1$ and $\omega_c \tau_0 \lesssim 1$. Since in high-mobility GaAs samples $\tau \gg \tau_0$, both of these conditions can be simultaneously met. The situation is markedly different in our MgZnO/ZnO sample where $\tau_q \lesssim \tau \approx 3.8$ ps and the above constraints are only marginally satisfied. Indeed, at $B = 0.7$ T we estimate $\omega_c \tau \approx 1.5$ and $\omega_c \tau_0 \approx 0.8$.

In summary, we have studied nonlinear magnetotransport in a Mg$_x$Zn$_{1-x}$O/ZnO heterostructure in the regime of weak direct currents. We have found that the differential resistivity acquires a correction $\delta r$ which is quadratic in direct current and decays exponentially with $1/B$. The analysis of the $B$-dependence of the curvature suggests that the nonlinear response is governed by a dc field-induced modification of the electron distribution function. The Dingle analysis in the regime of overlapping Landau levels reveals the quantum lifetime $\tau_q \approx 2.0$ ps, consistent with existing magnetotransport studies in similar Mg$_x$Zn$_{1-x}$O/ZnO heterostructures [11, 24, 27]. However, the regime of small direct currents explored in the present work also allowed us to obtain the inelastic relaxation time of $\tau_{in} \approx 40$ ps, which was not previously measured in Mg$_x$Zn$_{1-x}$O/ZnO heterostructures. Our study demonstrates that the nonlinear magnetotransport is a powerful technique to access scattering times in 2D systems not necessarily having high mobility. As such, the technique could be useful to investigate electron-impurity and electron-electron scattering in a broad variety of materials.

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