

Interplay between electron-hole and impurity scattering in HgTe-based quantum wells

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A 20-nm-wide (100)-oriented HgTe quantum well (QW) hosts a two-dimensional (2D) semimetal comprising both electrons and holes. In this study, we report that in addition to the previously observed quadratic temperature dependence of resistance, the system also displays an unexpected linear temperature dependence within specific top-gate voltage ranges. To account for this behavior, we extend the existing theoretical framework for temperature-dependent resistance in HgTe QW-based 2D semimetals with a focus on electron-hole scattering at low temperatures. Using the Boltzmann transport equation, we investigate the role of electron-hole interactions in this 2D semimetal. Our calculations reproduce a resistivity temperature dependence that aligns closely with experimental data. These findings establish this system as a robust platform for exploring interaction-limited transport regimes in a two-component plasma, particularly in the presence of disorder.

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I. INTRODUCTION

Analyzing various scattering mechanisms across different temperature regimes is essential for understanding the temperature dependence of a material's conductivity. At low temperatures, the dominant scattering processes are electron-impurity and interparticle (electron-electron or electron-hole) interactions. In Galilean-invariant systems with parabolic electron dispersion and a small Fermi surface, electron-electron scattering does not influence conductivity due to the conservation of total momentum during collisions [1].

However, it becomes particularly interesting to study systems in which Galilean invariance is broken, allowing interparticle scattering to significantly affect conductivity—especially at high temperatures. In such cases, electron-electron interactions can transpire in the transport properties through several mechanisms: (1) specific Fermi surface geometries that permit Umklapp scattering [1]; (2) electron-hole compensation in graphene and two-dimensional (2D) semimetals [2–5]; (3) multisubband systems with differing effective masses and impurity scattering times [6–10]; and (4) 2D system with linear spectrum [11].

Recently, quantum wells based on the Cd-HgTe/HgTe/CdHgTe structure have been actively studied both experimentally and theoretically, mainly due to their unique properties as topological insulators [12–17]. The

physical properties of CdHgTe/HgTe/CdHgTe quantum wells (QWs) are strongly affected by the QW width and orientation with respect to the growth axis. Experimentally, it has been established that above a critical QW width, HgTe QWs host a 2D topological insulator [12]. In contrast, for sufficiently thick HgTe QWs, the valence band overlaps with the conduction band minimum, leading to the coexistence of electrons and holes within the same QW—a semimetal regime [4,5,18–20]. Under the action of external uniform electric field, holes and electrons move in the opposite directions and their collisions strongly affect the HgTe QW conductivity at low temperatures leading to T^2 dependence of the resistivity [5]. It is important to note that the statistical properties of the charge carriers can significantly influence transport behavior. In particular, if one type of carriers follows Boltzmann statistics while the other obeys Fermi-Dirac statistics, the resulting particle-particle scattering can lead to a resistivity scaling as $\rho \sim T^{3-3.5}$. This temperature dependence has recently been observed in HgTe gapless quantum wells containing both heavy and Dirac-like holes [9].

Another important question is whether disorder or impurity scattering can modify the temperature dependence of resistivity when it is primarily governed by particle-particle collisions. In the presence of sufficiently strong disorder, the temperature behavior of resistivity in a semimetal can be significantly altered. Specifically, in a two-dimensional semimetal with smooth potential fluctuations, theory predicts that resistivity may decrease with increasing temperature due to enhanced percolative transport of electrons and holes across the sample [21].

Short-range disorder is also expected to influence resistivity by affecting electron-hole scattering. However, this effect has not yet been thoroughly investigated. The 20-nm-wide HgTe quantum well, which hosts a 2D semimetal, offers a

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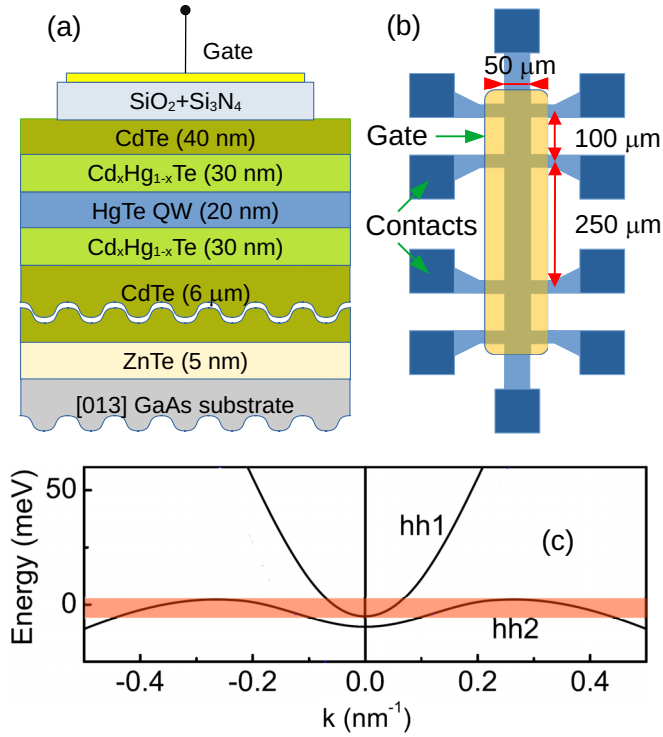


FIG. 1. (a) Layer-by-layer structure of the quantum well; (b) top view of the sample; and (c) schematic representation of the band spectrum of a 20-nm HgTe QW. The area where the conduction and valence bands overlap is highlighted.

versatile and tunable platform for exploring regimes where disorder impacts transport dominated by interparticle interactions.

Here, we experimentally demonstrate that at low temperatures, HgTe QWs in the semimetallic regime exhibit either a T^2 or linear temperature dependence of resistance, depending on the applied top-gate voltage. We attribute these behaviors to effective electron-hole scattering within the QW. In the following, we present detailed measurements of the temperature-dependent resistivity and develop a theoretical model that captures the key features of the observed behavior.

II. EXPERIMENT

The samples used in the experiment were made on the basis of 20-nm HgTe QWs with the (100) orientation, grown using the technology described earlier ([18,19] and the references therein). A schematic section of the QW is shown in Fig. 1(a). The experimental samples were standard Hall bars equipped with an electrostatic gate with a width of $W = 50 \mu\text{m}$ and a distance between voltage probes of $L = 100 \mu\text{m}$ and $L = 250 \mu\text{m}$ [Fig. 1(b)]. Using an electrostatic gate, the concentration of holes and electrons in the quantum well could be varied over a wide range. The measurements were carried out at temperatures of (0.2–10) K and in magnetic fields up to 5 T using standard phase detection techniques. The signal frequency was 6–12 Hz, and the driving currents were on the order of 1–10 nA to avoid heating effects.

Figure 2 shows the dependencies of the concentration and mobility of electrons and holes on the gate voltage at

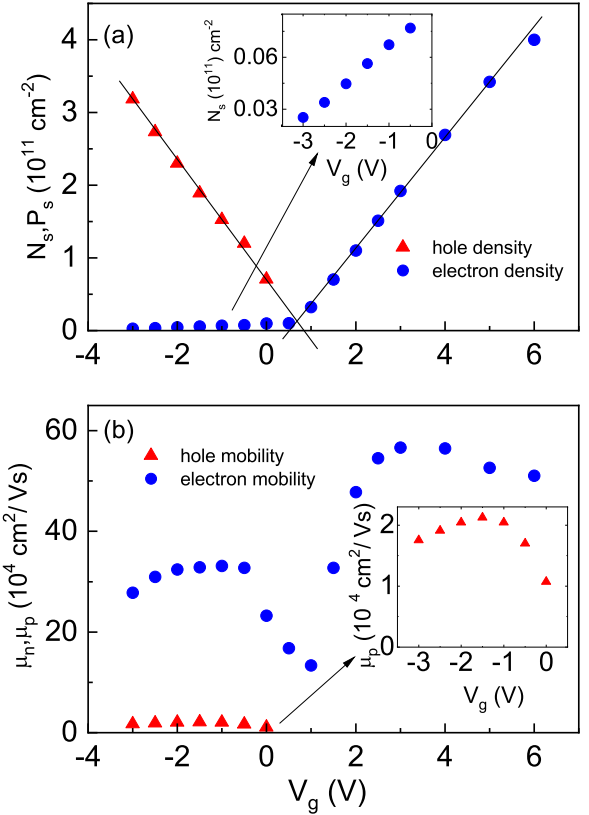


FIG. 2. (a) Gate voltage dependence of the density of 2D holes and 2D electrons in a 20-nm (100) HgTe QW. Inset: magnified gate voltage dependence of the electron density in the interval from -0.5 to -3 V; (b) gate voltage dependence of the mobility of 2D holes and 2D electrons in the 20-nm (100) HgTe QW. Inset: magnified gate voltage dependence of the hole mobility in the interval from 0 to -3 V. $T = 200$ mK.

$T = 200$ mK, obtained using the following procedure. At different values of gate voltage and in the classical magnetic field range near $B = 0$, the diagonal and Hall resistivity tensor components were measured as functions of magnetic field. In two-component systems such as semimetals, the low field $\rho_{xx}(B)$ is parabolic, while $\rho_{xy}(B)$ has a peculiar N-shaped appearance. As an example, Fig. 3 shows a pair of such dependencies for gate voltage $V_g = -2$ V. Each such pair of experimental curves was self-consistently fitted with the Drude model for a two-component system (e.g., Ref. [22]) with four fitting parameters N_s , P_s , μ_n , and μ_p (for more details, see Ref. [18]). The magnetoresistance behavior for $V_g > 0.7$ V implies a single-component, exclusively electron transport. The presence of holes in this region is undetectable.

As can be seen, in the gate voltage range $-3 \text{ V} \leq V_g \leq 0.7 \text{ V}$ the QW contains both two-dimensional electrons and holes; i.e. a two-dimensional semimetal is realized. As in other previously studied wide HgTe QWs with surface orientations (013) and (112), the main reason for the formation of a semimetal in the 20-nm (100) HgTe QW is the indirect overlap of the conduction band and valence band, caused by the deformation of HgTe due to small differences in lattice constants of HgTe and CdTe [Fig. 1(c)]. In a 20-nm (100) HgTe QW, this band overlap is relatively small, 1–1.5 meV. When

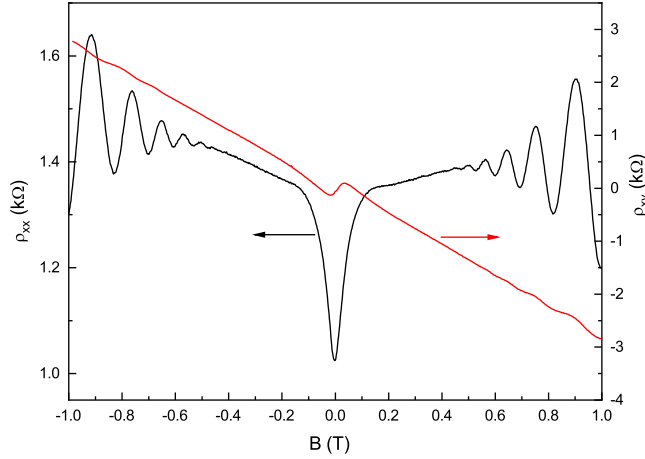


FIG. 3. The longitudinal ρ_{xx} and diagonal ρ_{xy} resistivities as functions of magnetic field for $V_g = -2$ V at $T = 0.2$ K.

the gate voltage changes from $+0.7$ to -3 V, the measured hole density to electron density ratio P_s/N_s changes from 1 to approximately 10^2 . The concentrations of electrons and holes at the charge neutrality point (CNP) ($V_g = +0.7$ V): $N_s = P_s \approx 1.2 \times 10^{10} \text{ cm}^{-2}$ [20].

Figure 4 shows the resistivity as a function of gate voltage [$\rho(V_g)$] at zero magnetic field ($B = 0$) and temperatures ranging from 0.2 to 10 K [34]. The $\rho(V_g)$ curve exhibits a peak that, at low temperatures, aligns with the CNP. However, as temperature increases, the peak diminishes in amplitude and shifts toward lower gate voltages.

Furthermore, as illustrated in Fig. 5, the gate voltage modulates the temperature dependence of the resistance, leading to an inversion effect. Specifically, in the gate voltage range $-2.9 \text{ V} < V_g < -0.5 \text{ V}$ —corresponding to a semimetallic regime where holes dominate over electrons—the resistivity increases linearly with temperature ($\rho \sim T$), with a transition to a quasiparabolic dependence at higher negative gate biases [Fig. 5(a)].

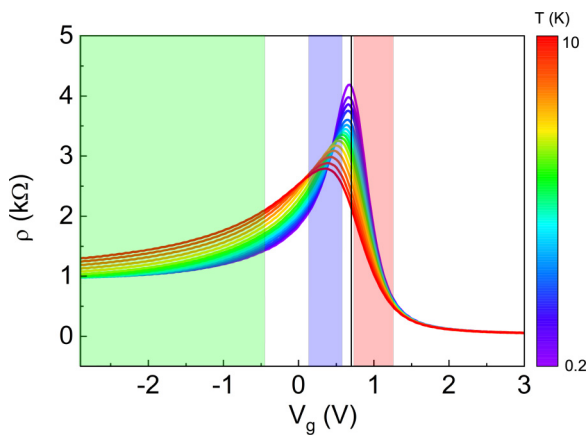


FIG. 4. Gate voltage dependence of resistivity ρ at $B = 0$ and temperatures $T = 0.2, 0.5, 0.7, 1, 1.5, 2, 2.5, 3, 3.5, 4.2, 5, 6, 7, 8, 9$, and 10 K. The vertical line at $V_g = 0.7$ V marks the approximate position of the CNP. The density windows with different T regimes are marked by a colored shading.

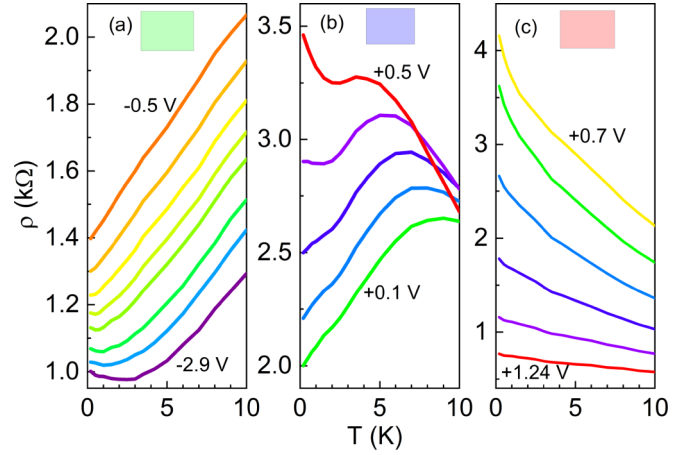


FIG. 5. Temperature dependence of resistivity ρ at $B = 0$ at different gate voltage ranges. The corresponding density windows for different temperature regimes, shown in Fig. 3, are marked by colored rectangles: (a) semimetal, from linear to parabolic T dependence: $V_g = -0.5, -0.7, -0.9, -1.1, -1.3, -1.7, -2.1$, and -2.9 V. (b) region of T -dependence inversion: $V_g = 0.5, 0.4, 0.3, 0.2$, and 0.1 V. (c) From 2DEG to CNP: $V_g = 1.24, 1.1, 1.0, 0.9, 0.8$, and 0.7 V.

In the vicinity of the CNP—gate voltages between 0.1 and 0.5 V—the temperature dependence of resistance is highly nonmonotonic [Fig. 5(b)].

Finally, to the right of the CNP ($V_g > 0.7$ V), where only the two-dimensional electron gas (2DEG) is present in the quantum well, the resistance increases as temperature decreases [Fig. 5(c)]. This effect is more pronounced at lower electron concentrations.

In conclusion of this section, we address the potential influence of a temperature-dependent band structure on our results discussed in papers [23–25]. While significant band gap renormalization is known to occur in HgTe QWs at elevated temperatures ($T > 70$ K), its effect is negligible in our low-temperature regime ($T < 10$ K) for several reasons. First, the Quantum Hall Effect and Shubnikov-de Haas oscillations, which are highly sensitive to the band structure and carrier densities, remain well defined and show no significant changes in HgTe wells at temperatures below 70 K [26,27]. This indicates that the electronic spectrum is effectively temperature-independent in our experimental range. Second, a thermally activated change in the band gap would lead to a dominant activation-type dependence of the resistivity (i.e., resistance decreasing with temperature), as observed in gapped 8-nm wells [28]. In contrast, such an activation law is absent in our semimetallic 20-nm wells; here, the resistance increases with temperature, which is the opposite of what a gap opening would cause. Finally, a comprehensive analysis of various experiments and recent theoretical calculations [25] suggests that a significant, demonstrable temperature dependence of the band gap in HgTe QWs below 70 K remains elusive. Therefore, we conclude that the observed crossover in the temperature scaling of the resistivity is unambiguously governed by the interplay of electron-hole and impurity scattering, rather than by a temperature-dependent band structure.

In the subsequent analysis, we focus on the theoretical interpretation of the $\rho(T)$ dependence in the gate voltage region corresponding to a two-dimensional semimetal.

III. THEORETICAL MODEL

The theoretical model under study is a 2D electron-hole gas. We assume that the residual conductivity at zero temperature is determined by the particle-impurity scattering, whereas the low-temperature corrections to the semimetal conductivity come mainly from highly mobile electrons scattered off the low-mobile holes. We use the term “low temperatures” in the sense that the region under study (0.2–10) K is low in comparison with Debye phonon energy and one can disregard the electron-phonon scattering processes. In this paper, we pay theoretical attention to the gate voltage region $-3 \text{ V} < V_g < -0.5 \text{ V}$, where the sample resistance demonstrates either T or T^2 behavior [Fig. 5(a)]. Theoretical study of other behaviors [Figs. 5(b) and 5(c)] is beyond the scope of this paper.

The key idea of our theoretical model is as follows. The type of hole motion is determined by the relation between the hole mean free path, $l_h = v_h \tau_h$ (v_h is a hole Fermi velocity and τ_h is a hole momentum relaxation time due to scattering off impurities), and the wave vector $\mathbf{q}$ describing the momentum transferring between hole and electron under individual collision. Its value is determined by the temperature, $q(T) \sim \sqrt{2m_h T}$. Thus, the limit $q(T)l_h < 1$ corresponds to diffusive hole motion, whereas $q(T)l_h > 1$ determines the quasiballistic regime of hole motion [29]. The mean free path is determined by the hole density that in turn is controlled by the gate voltage applied, $l_h(V_g)$.

At gate voltages $V_g \sim -0.5 \text{ V}$, the hole density is low enough, but much larger than the electron one [Fig. 2(a)] and holes move diffusively, $q(T < 10 \text{ K}) \cdot l_h(V_g \sim -0.5 \text{ V}) < 1$ and electrons scattered off these holes demonstrate the linear-in- T correction to the sample resistivity [Fig. 5(a)]. With a further gate voltage lowering till $V_g \sim -3 \text{ V}$, the hole density is increased converting the hole motion to the quasiballistic regime, $q(T > 1 \text{ K}) \times l_h(V_g \sim -3 \text{ V}) > 1$. Thus, electrons scattered off the quasiballistic holes result in the quadratic-in- T temperature correction to the sample resistivity at gate voltage $V_g \sim -3 \text{ V}$ [Fig. 5(a)]. At the same time, we assume that electrons, being highly mobile particles [Fig. 2(b)], are in the quasiballistic regime of their motion over all the range of gate voltages corresponding to the semimetal regime, i.e., from -0.5 to -3 V .

At low temperatures, when the relaxation rate of particle momentum due to the scattering on impurities is $1/\tau_{e,h} \gg gT^2/E_F$ (here, gT^2/E_F is a particle-particle collision rate, with g being the effective particle-particle interaction constant), the interparticle Coulomb scattering can be considered as a correction to the residual conductivity determined by the particle collisions with impurities [30]. In this paper, we consider the lowest order corrections on the electron-hole Coulomb interaction potential to the electron conductivity and resistivity. Below, we apply Boltzmann transport equation approach to calculate the low-temperature corrections to the electron conductivity induced by the electron scattering off holes.

A. Theory of electron conductivity correction caused by Coulomb interaction with holes

We start from the Boltzmann equation for electron distribution function $f_{\mathbf{p}}$ written as

$$\frac{\partial f_{\mathbf{p}}}{\partial t} + \mathbf{F} \cdot \frac{\partial f_{\mathbf{p}}}{\partial \mathbf{p}} = Q_i\{f_{\mathbf{p}}\} + Q_{eh}\{f_{\mathbf{p}}\}, \quad (1)$$

where $\mathbf{F} = e\mathbf{E}$ is a static force affecting electrons. The electron-impurity collision integral is $Q_i\{f_{\mathbf{p}}\} = 2\pi n_i u_0^2 \sum_{\mathbf{p}'} (f_{\mathbf{p}'} - f_{\mathbf{p}}) \delta(\epsilon_{\mathbf{p}'} - \epsilon_{\mathbf{p}})$, whereas the electron-hole collision integrals read

$$\begin{aligned} Q_{eh}\{f_{\mathbf{p}}\} = 2\pi \sum_{\mathbf{p}', \mathbf{k}, \mathbf{k}'} |U_{\mathbf{p}'-\mathbf{p}}|^2 & [(1 - f_{\mathbf{k}})(1 - f_{\mathbf{p}})f_{\mathbf{k}'}f_{\mathbf{p}'} \\ & - (1 - f_{\mathbf{k}}')(1 - f_{\mathbf{p}'})f_{\mathbf{k}}f_{\mathbf{p}}] \delta(\epsilon_{\mathbf{k}'} + \epsilon_{\mathbf{p}'} - \epsilon_{\mathbf{k}} - \epsilon_{\mathbf{p}}) \\ & \times \delta_{\mathbf{k}'+\mathbf{p}', \mathbf{k}+\mathbf{p}}. \end{aligned} \quad (2)$$

Here, $\mathbf{p}$ refers to an electron momentum, $\mathbf{k}$ is a hole momentum, n_i is an impurity density, u_0 is a strength of short-range impurity potential, $u(\mathbf{r}) = u_0 \delta(\mathbf{r})$, $U_{\mathbf{q}}$ is Coulomb interaction potential, $\epsilon_{\mathbf{p}} = p^2/2m_e$ is an electron dispersion, and $\epsilon_{\mathbf{k}} = (\mathbf{k} \pm \mathbf{k}_0)^2/2m_h - \Delta$ is a hole dispersion [Fig. 1(c)]. We will ignore here the intervalley scattering both in the particle-impurity and particle-particle scattering channels; thus, the shift of hole valleys by $\pm \mathbf{k}_0$ does not play the role, and further we count the hole momenta from this value, $\mathbf{k} \pm \mathbf{k}_0 \rightarrow \mathbf{k}$. The doubling of single-valley hole density due to two valleys will be accounted in the total hole density. Here and below, we put $\hbar = 1$ and restore it in the final expressions. Further, we consider the electron and hole scattering off short-range impurities, and the corresponding scattering times are assumed to be independent from the corresponding particle energy. In this case, we use the relaxation time approximation for the electron-impurity and hole-impurity scattering processes $Q_i\{f_{\mathbf{p}(\mathbf{k})}\} = -(f_{\mathbf{p}(\mathbf{k})} - n_{\mathbf{p}(\mathbf{k})})/\tau_{e(h)}$. Here, $n_{\mathbf{p}(\mathbf{k})}$ is an equilibrium Fermi distribution function of electrons (holes) and $\tau_{e(h)}$ are particle-impurity momentum relaxation times. The distribution function is expanded into the powers of external EM field as $f_{\mathbf{p}} = n_{\mathbf{p}} + \delta f_{\mathbf{p}}$, where $\delta f_{\mathbf{p}}$ is a first-order correction with respect to electric field $\mathbf{E}$. The Coulomb interaction is considered as a correction to the residual scattering off impurities. Thus, $\delta f_{\mathbf{p}} = \delta f_{\mathbf{p}}^0 + \delta f_{\mathbf{p}}^C$, where $\delta f_{\mathbf{p}}^C$ can be found via a successive approximation to be applied to the right-hand side of Eq. (1) [1].

Standard calculations [1] result in the following correction to electron conductivity:

$$\begin{aligned} \delta\sigma_{xx}^e = 2\pi e^2 \frac{\tau_e}{m_e} \left(\frac{\tau_e}{m_e} + \frac{\tau_h}{m_h} \right) & \times \int_0^\infty \frac{q dq}{2\pi} \frac{q^2 |U_{\mathbf{q}}|^2}{2} \int_{-\infty}^{+\infty} d\omega \\ & \times \frac{\text{Im} \Pi^e(-\mathbf{q}, -\omega) \text{Im} \Pi^h(\mathbf{q}, \omega)}{4\pi^2 T \sinh^2(\omega/2T)}, \end{aligned} \quad (3)$$

where

$$\Pi^h(\mathbf{q}, \omega) = \sum_{\mathbf{k}} \frac{n_{\mathbf{k}} - n_{\mathbf{k}+\mathbf{q}}}{\epsilon_{\mathbf{k}} - \epsilon_{\mathbf{k}+\mathbf{q}} + \omega + i0} \quad (4)$$

is a hole polarization operator. Electron polarization operator $\Pi^e(\mathbf{q}, \omega)$ has a similar form. Expression in Eq. (3) is a temperature-dependent electron conductivity correction due to the electron-hole scattering in a 2D semimetal. The residual resistance at $T = 0$ is determined by the electron and hole scattering via impurities. Thus, the temperature behavior of the sample resistivity is determined by the temperature dependence of conductivity corrections found above. It is expressed as

$$\frac{\rho(T) - \rho_0}{\rho_0} \approx -\rho_0 \delta\sigma_{xx}(T), \quad (5)$$

where $\rho_0 = \rho(T = 0)$ is the residual sample resistance at zero temperature. The found conductivity correction [Eq. (3)] tends to zero at $T = 0$. In our particular case, we approximate $\rho_0 \approx \rho(T = 0.2 \text{ K})$. With growing the temperature, expression in Eq. (3) displays either quadratic or linear-in- T behavior, depending on the regime of hole motion.

A particular form of interparticle scattering potential $U_{\mathbf{q}}$ is not well known, and to compare Eq. (3) with experiment, we must take into account the following features of our experimental structure. First, it should include the possible spatial separation of electrons and holes within the quantum well due to the applied gate voltage. Second, it has to take into account the finite quantum well width. Third, it should take into account the possible screening processes both due to the mobile carriers and due to the polarizability of quantum well material. Thus, we apply the general form of the Coulomb interacting potential suggested by Rytova [31] (see also Refs. [32,33]), which accounts for the finite quantum well width and both types of screening effects pointed out above. Below, we compare theoretical expressions for resistivity correction with experimental data both in the quasiballistic and diffusive hole motion with two types of interparticle interaction potentials.

B. Quasiballistic regime of hole motion

In a quasiballistic regime for electrons and holes, the polarization operators read [29]

$$\text{Im } \Pi^h(\mathbf{q}, \omega) = -\frac{m_h}{2\pi} \frac{\omega}{v_h q}, \quad \text{Im } \Pi^e(-\mathbf{q}, -\omega) = \frac{m_e}{2\pi} \frac{\omega}{v_e q}. \quad (6)$$

Substituting these expressions into Eq. (3), taking the integrals over ω , one finds

$$\delta\sigma_{xx}^e = -\frac{e^2 \tau_e T^2}{3(2\pi)^2 m_e} \frac{\tau_e m_h + \tau_h m_e}{v_e v_h} \int_0^{2p_0} q dq |U_{\mathbf{q}}|^2, \quad (7)$$

where $p_0 = \min(p_e, p_h)$. This expression describes the electron conductivity correction under the quasiballistic motion of elections and holes. It scales as T^2 regardless the form of interaction potential $U_{\mathbf{q}}$. For comparison with the experiment, we calculated the resistivity $\rho(T)$. A comparison of resistivity correction [Eq. (5)] together with conductivity expression [Eq. (7)] with experimental data is presented in Fig. 6 (red curve). Our theoretical model does not well coincide with the experiment at extremely low temperatures ($T < 1 \text{ K}$) in the quadratic-in- T behavior of semimetal resistivity in Fig. 6. We believe that this discrepancy may be due to the combined effect of the weak-localization and electron-electron

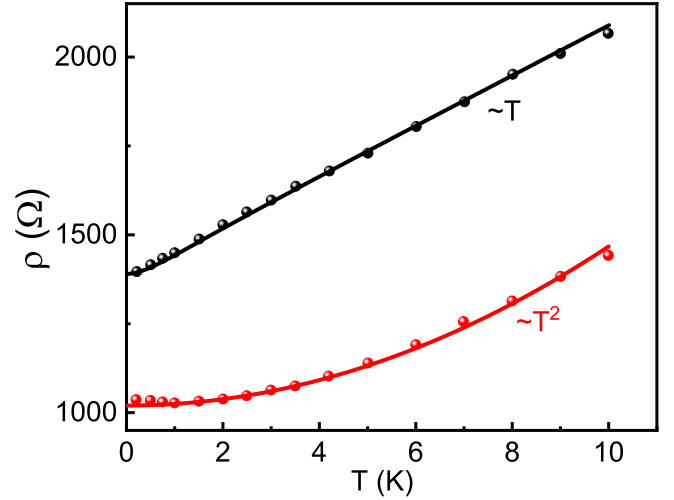


FIG. 6. Red curve—Quadratic temperature dependence of resistivity $\rho(T)$ at gate voltage $V_g = -2.1 \text{ V}$ using Eq. (7) with parameters $N_e = 4.47 \times 10^9 \text{ cm}^{-2}$, $N_h = 2.3 \times 10^{11} \text{ cm}^{-2}$, $\mu_e = 3.24 \times 10^5 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, and $\mu_h = 2.05 \times 10^4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. Black curve—Linear temperature dependence of resistivity $\rho(T)$ at gate voltage $V_g = -0.5 \text{ V}$ using Eq. (11) with parameters $N_e = 7.7 \times 10^9 \text{ cm}^{-2}$, $N_h = 1 \times 10^{10} \text{ cm}^{-2}$, $\mu_e = 3.27 \times 10^5 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, and $\mu_h = 1.69 \times 10^4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. Red and black circles—corresponding experimental dependence.

interaction corrections to the conductivity of highly mobile electrons scattered off the hole gas subsystem. For a disordered 2D metal, the quantum correction to the conductivity can be expressed as the sum of two contributions arising from weak localization and electron-electron interactions: $\delta\sigma = \delta\sigma_{\text{loc}} + \delta\sigma_{\text{int}}$. The weak-localization correction is given by

$$\delta\sigma_{\text{loc}} = \alpha_{\text{loc}} \frac{e^2}{h\pi} \ln \left(\frac{k_B T}{T_0} \right), \quad (8)$$

where the coefficient α_{loc} takes the value $+1$ for weak localization and $-\frac{1}{2}$ for antilocalization. In the diffusion regime ($T\tau \gg 1$), the electron-electron interaction contribution to the conductivity can be approximated as

$$\delta\sigma_{\text{int}} = \alpha_{\text{int}} \frac{e^2}{h\pi} \left(\frac{k_B T \tau}{\hbar} \right), \quad (9)$$

where τ is the momentum relaxation time and α_{int} is the interaction coefficient. Experimental observations show that owing to the combined quantum corrections dominated by e-e interaction the conductivity decreases logarithmically with the temperature lowering. A corresponding increase in resistivity $\delta\rho \sim -\delta\sigma \rho_0^2$ of approximately 2% could account for the observed discrepancy between experiment and theory in the 0.2–1 K temperature range [Fig. 6 (red curve)]. A theoretical analysis of quantum corrections effects is beyond the Boltzmann equation approach developed here.

C. Diffusive regime of hole motion

In the diffusive limit of hole motion, $D_h q^2 \tau_h \ll 1$ and $\omega \tau_h \ll 1$. In this limit, the hole polarization operator is [29]

$$\text{Im}\Pi^h(\mathbf{q}, \omega) = -\frac{m_h}{2\pi} \frac{\omega D_h q^2}{\omega^2 + (D_h q^2)^2}. \quad (10)$$

Thus, the conductivity correction can be written in the form

$$\delta\sigma_{xx}^e = -\frac{e^2 \tau_e}{(2\pi)^4} \frac{(\tau_e m_h + \tau_h m_e)}{p_e} 2T \int_0^{1/l_h} q^2 |U_{\mathbf{q}}|^2 dq \times \int_{-1/2T\tau_h}^{1/2T\tau_h} \frac{x^2 dx}{\sinh^2(x)} \frac{\beta_q}{(x^2 + \beta_q^2)}, \quad (11)$$

where $\beta_q = D_h q^2 / 2T = (ql_h)^2 / 2(T\tau_h)$ and $l_h^2 = D_h \tau_h$ is a hole diffusive length. In the diffusive limit $T\tau_h \ll 1$ of hole motion, Fig. 6 compares the theoretical expression [Eq. (11)] (black curve) with experimental data. Despite the complexity of Eq. (11) as a function of temperature, we observe good agreement with a linear dependence on T .

To theoretically confirm that Eq. (11) indeed exhibits linear behavior—particularly in the temperature range $2\text{ K} < T < 10\text{ K}$ —we analyzed a simplified model of interparticle interaction $U_{\mathbf{q}}$. As demonstrated in the Appendix, Eq. (11) reduces to a linear dependence on T for specific parameter values.

IV. CONCLUSION

We carried out the experimental and theoretical studies of HgTe-based QW structure in the semimetal regime. It was shown that the experimental study demonstrates either linear- or quadratic-in-temperature corrections to the semimetal resistivity, depending on the top gate voltage applied to the experimental structure. We suggested a theoretical model and developed the corresponding theoretical description of the experimental system that demonstrates a reasonable agreement with the experiment. At the same time, the nonsemimetal domains of gate voltages, close to the charge neutrality point [Figs. 5(b) and 5(c)] are not described via the presented theoretical model and still require a theoretical grounding.

Our study explores a regime in condensed matter physics: non-Galilean systems, where electron-electron (e-e) and electron-hole (e-h) collisions dominate resistivity—a stark contrast to Galilean-invariant systems. This research has only recently become feasible due to advances in fabricating ultraclean semimetals where e-e/e-h scattering exhibits a clear T^2 dependence. Specifically, the question we address here is how disorder modifies e-h scattering in such systems. Beyond its immediate implications, this framework opens avenues for investigating e-h scattering in other semimetals—such as graphene, 3D topological insulators, and Weyl semimetals—promising deeper understanding of transport phenomena in these materials.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [34].

APPENDIX

Here, we show that expression in Eq. (11) contains the linear-in- T dependence. In the diffusive regime, $T\tau_h \ll 1$, there are two possible cases $T \ll D_h q^2 \ll 1/\tau_h$ and $D_h q^2 \ll T \ll 1/\tau_h$. In the first case $\beta_q \gg 1$, whereas in the second case $\beta_q \ll 1$.

In the latter case, $\beta_q \ll 1$, integrals in Eq. (11) can be estimated as

$$\int_{-1/2T\tau_h}^{1/2T\tau_h} \frac{x^2 dx}{\sinh^2(x)} \frac{\beta_q}{(x^2 + \beta_q^2)} \sim \beta \int_{-\infty}^{\infty} \frac{dx}{x^2 + \beta_q^2} = \pi, \quad \delta\sigma_{xx}^e = -\frac{e^2 (\tau_e T)}{(2\pi)^3} \frac{\tau_e m_h + \tau_h m_e}{p_e} \int_0^{\sqrt{T/D_h}} q^2 dq |U_{\mathbf{q}}|^2. \quad (\text{A1})$$

Depending on the value of last integral over q , the conductivity correction acquires the different temperature behavior. To demonstrate it, we apply the simplified Rytova-Keldysh interaction potential of the form $U_{\mathbf{q}} = 2\pi e^2 / q(1 + 2\pi\alpha q)$, where $\alpha \sim d(\kappa - 1)/4\pi$ is a quantum well polarizability and d is quantum well width. Thus, the q integral reads

$$\int_0^{\sqrt{T/D_h}} q^2 dq |U_{\mathbf{q}}|^2 = (2\pi e^2)^2 \int_0^{\sqrt{T/D_h}} \frac{dq}{(1 + 2\pi\alpha q)^2} = (2\pi e^2)^2 \frac{\sqrt{T/D_h}}{1 + 2\pi\alpha \sqrt{T/D_h}}. \quad (\text{A2})$$

As a result, if $2\pi\alpha \sqrt{T/D_h} \gg 1$, then Eq. (A2) is not dependent on temperature, resulting to linear-in- T behavior of conductivity correction [Eq. (A1)]. The inequality $2\pi\alpha \sqrt{T/D_h} \gg 1$ corresponds to $T \gg 4D_h/d^2(\kappa - 1)^2 \sim 10^{-3}\text{ K}$, which is definitely satisfied in our experimental structures.

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