Signatures of an anomalous Nernst effect in a mesoscopic two-dimensional electron system

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We investigate the Nernst effect in a mesoscopic two-dimensional electron system (2DES) at low magnetic fields, before the onset of Landau level quantization. The overall magnitude of the Nernst signal agrees well with semiclassical predictions. We observe reproducible mesoscopic fluctuations in the signal that diminish significantly with an increase in temperature. We also show that the Nernst effect exhibits an anomalous component that is correlated with an oscillatory Hall effect. This behavior may be able to distinguish between different spin-correlated states in the 2DES.

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The application of a thermal gradient (∇T) across a solid leads to the diffusion of carriers from the hot to cold reservoir. The temperature difference (ΔT) across the system results in a longitudinal (parallel to ∇T) voltage difference (V_{xx}) across the system—the Seebeck effect. This yields the diagonal component of the thermopower tensor ($\tilde{S}$), $S_{xx} = V_{xx}/\Delta T$. In a perpendicular magnetic field (B), the carrier trajectories are bent, resulting in a transverse voltage (V_{xy}) in a direction mutually perpendicular to ∇T and B. This is known as the Nernst-Ettingshausen effect. The corresponding off-diagonal term of $\tilde{S}$ is given by $S_{xy} = -S_{yx} = V_{xy}/\Delta T$. The Nernst effect is highly sensitive to the structure of the Fermi surface as well as the carrier mobility.[1] This makes it a particularly efficient probe to study a variety of strongly correlated systems such as Kondo lattices[2] and graphene field effect transistors in the quantum Hall regime.[3,4] However, there are surprisingly limited studies of the Nernst effect in the ubiquitous two-dimensional electron gas (2DEG).[5–7]

As a consequence of the electron-hole symmetry in an ideal single band metal, a thermal gradient gives rise to equal heat currents associated with both electrons and holes. Thus, no net electric field is generated across the metal, and the thermopower (TP) is zero. However, in real metallic systems a nonzero (small) TP is found to exist at zero magnetic fields. This is also the case for a bulk 2DEG at zero B.[5,6] At high B, in the regime of Landau level quantization, both S_{xx} and S_{xy} are found to be periodic in $1/B$.[5,6] This is a direct reflection of the oscillating density of states of the 2DEG. In particular, S_{xx} has been used to study reentrant insulating states of a two-dimensional (2D) hole gas in the quantum Hall regime.[8] Such studies of the thermoelectric properties of 2D systems reveal information that is not accessible from standard resistance and/or conductance measurements.

In contrast with high-field studies of the magnetothermoelectric properties of two-dimensional electron systems (2DESs) in which the Landau levels are resolved, thermoelectric properties in the low-field limit remain relatively unexplored, barring some studies of weak localization in TP.[9] Interestingly, Hall measurements of mesoscopic 2DESs at such low magnetic fields (less than 5 mT) have revealed an anomalous Hall effect (AHE) in which the Hall coefficient (γ_H) oscillates with the carrier density (n_{2D}) with a period commensurate with that of the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction.[10] This, along with other studies of nonequilibrium transport[11,12] and longitudinal TP in 2DESs point strongly toward the existence of localized spins and tunable magnetic phases in mesoscopic 2DESs.[13] A natural question to ask is whether the thermoelectric counterpart of the Hall effect (i.e., the Nernst effect) is sensitive to these spin correlations.

In this Brief Report, we attempt to answer this question by exploring the low-temperature ($T < 0.5$ K), low-B ($B < 100$ mT) behavior of S_{xy} in a gate tunable mesoscopic 2DES. Superposed on an underlying semiclassical behavior of S_{xy}, we observe mesoscopic fluctuations that arise due to quantum interference phenomena. Furthermore, a comparison of density-dependent variations in S_{xy} with oscillations in γ_H suggests that the Nernst effect may be sensitive to spin effects in the system.

For these experiments we used a Si δ-doped GaAs/AlGaAs heterostructure with an 80-nm-thick spacer layer and an as-grown mobility of 3×10^6 cm^2/Vs. Figure 1(a) outlines the layout used to study the thermoelectric properties of the device. The gate FG is used to define a square 5 μm $\times$ 5 μm region where n_{2D}, and hence Fermi energy (ϵ_F), may be tuned continuously. The quantum point contacts (QPCs—Q_1 and Q_2) have a threefold functionality: (i) They serve as local thermometers that allow accurate determination of the temperature of the mesoscopic region (T_m), and consequently ΔT across the device (details of the calibration procedure can be found in Ref. 13); (ii) one-dimensional channels created by the QPCs serve as Hall-Nernst probes; and (iii) they are used to pinch off the 2DEG adjacent to the square region, thus ensuring that there are no parallel conduction paths. The QPCs were adjusted such that their contribution to TP was negligible. The temperature gradient across the mesoscopic device was established by passing a heating current [$I_h = 1$ μA, frequency (f) = 11.3 Hz] between contacts 4 and 5. The resultant T_m and ΔT were estimated to be 242 mK and 9 mK, respectively. Then, by measuring the thermoelectric signals, V_{xx} (between 1 and 3) and V_{xy} (between 2 and 6) at $2f$, we were able to estimate S_{xx} and S_{xy}. All measurements were carried out in a dilution refrigerator with a base electron temperature of ~70 mK.

Figure 1(b) shows the variation of conductance (G) with V_{FG} (bottom axis) and the corresponding n_{2D} (top axis) of the mesoscopic region. It is clear that the device is far from the strongly localized regime since $G > 10$ e^2/h

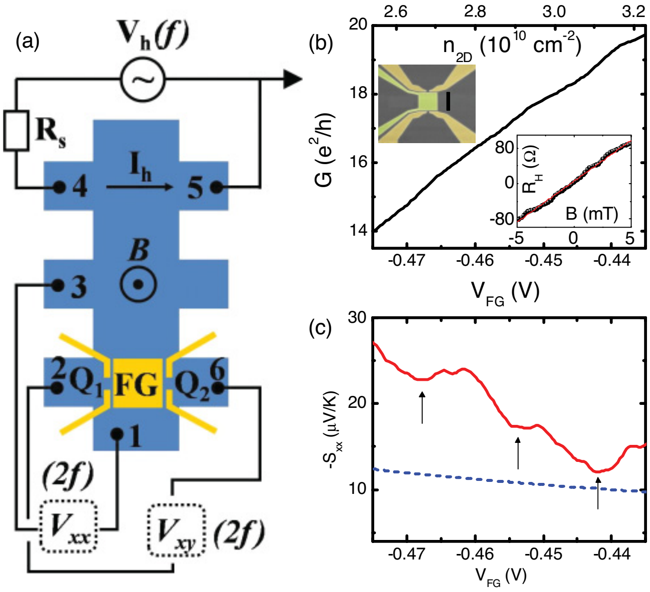

FIG. 1. (Color online) (a) Schematic of the layout used to measure the longitudinal and transverse components of thermopower. (b) Conductance (G) vs gate voltage (V_{FG}) (bottom axis). The corresponding number density (n_{2D}) is shown on the top axis. (Top inset) Scanning electron microscopy image of the device. The scale bar is 5 μm. (Bottom inset) A typical Hall trace showing the variation of Hall resistance (R_H) with B. (c) Longitudinal thermopower (S_{xx}) oscillations ($T_m = 242$ mK) as a function of V_{FG} (solid curve) and the expected S_{xx} from the free electron model (dashed line).

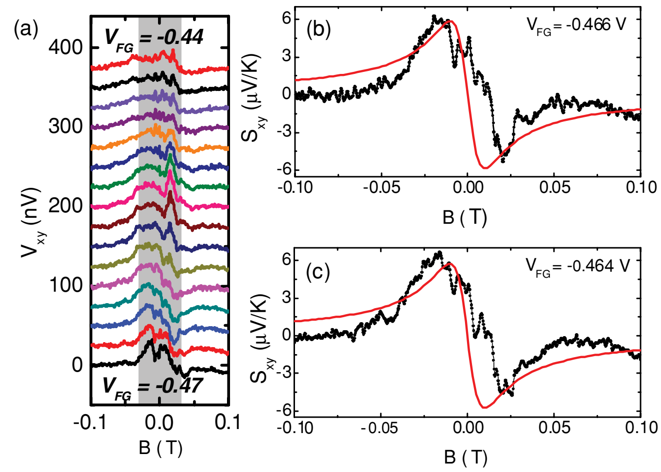

FIG. 2. (Color online) (a) Series of traces showing the variation of V_{xy} with B for V_{FG} ranging from -0.470 V(bottom trace) to -0.440 V (top trace). Curves have been offset by 25 nV for clarity. (b) and (c) Two individual traces from (a) showing the antisymmetric nature of $S_{xy}(B)$ along with clear mesoscopic fluctuations. Solid lines show traces expected from a semiclassical treatment of S_{xy} with $T_m = 242$ mK.

throughout. Thus, we maintain this V_{FG} range for subsequent thermoelectric studies. The top inset shows a scanning electron microscopy image of the device under study and the bottom inset shows a typical Hall trace used to estimate γ_H. Figure 1(c) shows oscillations in S_{xx} as a function of V_{FG}, which have been attributed to the existence of localized spins in the mesoscopic system.[13] The dips (marked by arrows) indicate the existence of a strong Kondo screened state. Between successive minima, S_{xx} is modulated by the RKKY interaction. The dashed line shows the calculated S_{xx} from the free electron model[5] to be lower than the experimentally observed values. This discrepancy becomes more evident as V_{FG} is made more negative, in line with our previous work.[13]

We now turn our attention to a detailed study of S_{xy} for $|B| < 100$ mT. Figure 2(a) shows the variation of V_{xy} with B at various V_{FG}. Figures 2(b) ($V_{FG} = -0.466$ V) and 2(c) ($V_{FG} = -0.464$ V) show two isolated traces. We note two important features: (i) The curves are antisymmetric in B, as is expected for the Nernst effect; and (ii) there exist prominent mesoscopic fluctuations riding the curves. Using Boltzmann transport theory, it has been shown that the diffusion component in this regime can be written as[14]

$$S_{xy} = -\alpha \frac{\pi^2 k_B^2 T}{3|e|\epsilon_F}\left(\frac{\omega\tau}{1+\omega^2\tau^2}\right), \qquad (1)$$

where k_B is the Boltzmann constant, T is the temperature (T_m in our case), e is the electronic charge, ϵ_F is the Fermi energy, ω is the cyclotron frequency, and τ is the momentum relaxation time. The prefactor (α) accounts for energy-dependent scattering and has been shown to be system dependent,[14] but is usually of the order unity. The solid lines in Figs. 2(b) and 2(c) are obtained using Eq. (1), where all the variables have been determined experimentally. The only free parameter, α, was fixed at $\alpha = 1.9$ to give magnitudes of S_{xy} that agree reasonably well with our experiments. Thus, we find that the overall magnitude of S_{xy} agrees with the semiclassical prediction for a 2DES. This is in contrast with a highly enhanced S_{xx} observed in these systems at zero magnetic fields.[13] This is not entirely surprising if one considers the source of the enhancement in TP to be related to spin entropy transfer, as observed in Kondo correlated quantum dots[15] and layered cobalt oxides.[16] Such a scenario would result in the enhancement of S_{xx} (the direction in which energy flow occurs), leaving S_{xy} essentially unaffected.

Mesoscopic fluctuations in electrical conductance have been studied in great detail in the past (for a review see Ref. 17). Here, we observe similar fluctuations in S_{xy}. These fluctuations are found to be particularly prominent for $|B| < 30$ mT [shaded region in Fig. 2(a)]. Figure 3(a) shows the high degree of reproducibility of these fluctuations for $V_{FG} = -0.466$ V (top trace) to -0.470 V (bottom trace). A smooth background was subtracted from the raw data to obtain ΔS_{xy} and enhance the clarity of the fluctuations. Figure 3(b) shows the fluctuations at significantly different V_{FG}. It is clear that the qualitative nature of the fluctuations is different for widely spaced V_{FG}, thus suggesting that they are related to quantum interference phenomena that are highly sensitive to the disorder layout in the mesoscopic region. They appear to be random in B, with no obvious periodicity. We find further evidence of the quantum origin of these fluctuations in their temperature dependence. As T_m is increased from 242 to 428 mK, the amplitude of the fluctuations is damped significantly [Fig. 3(c)]. To make this more quantitative, we plot the root mean square (rms) amplitude of the fluctuations ($\Delta S_{xy}^{\rm rms}$) as a function of T_m in Fig. 3(d). We find that ($\Delta S_{xy}^{\rm rms}$)

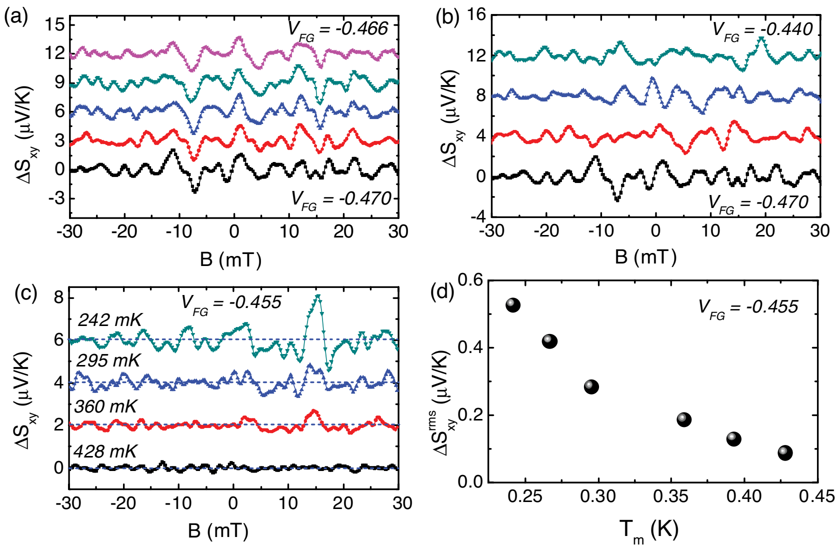

FIG. 3. (Color online) (a) Reproducible mesoscopic fluctuations in S_{xy} within a narrow range of V_{FG} from -0.470 V (bottom) to -0.466 V (top) in steps of 1 mV. Traces have been offset by 3 μV/K. (b) Qualitatively different nature of the fluctuations at widely spaced V_{FG} from -0.470 V (bottom trace) to -0.440 V (top trace) in steps of 10 mV (offset is 4 μV/K). (c) Damping of the fluctuations (for $V_{FG} = -0.455$ V) from $T_m = 242$ mK (top trace) to 428 mK (bottom trace). (d) Temperature dependence of the rms values of the fluctuations ($\Delta S_{xy}^{\rm rms}$) in (c).

decays rapidly with T_m and almost vanishes around $T_m \sim$ 500 mK. The insensitivity of $\Delta S_{xy}^{\rm rms}$ to V_{FG} and its extreme sensitivity to T_m make it tempting to draw analogies with universal conductance fluctuations (UCF).[18] Although there have been reports of the observation of universal thermopower fluctuations,[19] a more detailed analysis is required to study correlations (if any) between UCF and mesoscopic fluctuations in S_{xy}. Nevertheless, we can certainly say that S_{xy} is highly sensitive to quantum interference effects in the 2DES.

In the presence of magnetic phases, we would expect spin-dependent scattering processes to significantly alter the transport properties of the 2DES. Thus, systematically probing the dependence of S_{xy} on V_{FG} may allow us to directly investigate spin-correlated states in our mesoscopic system. To do so, we first perform electrical Hall measurements (along the lines of Ref. 10) at low magnetic fields (<5 mT) for various V_{FG}. A typical Hall trace is shown in the lower inset of Fig. 1(b). Figure 4(a) shows clear oscillations in γ_H as a function of V_{FG} (bottom axis). These oscillations can be explained on the basis of a model in which a quasiperiodic array of localized spins in the 2DES interacts via the RKKY interaction.[10,11] The strength of the RKKY interaction oscillates as a function of the Fermi wave vector (k_F) as $J(k_F) \propto \cos(2k_F R)/(k_F R)^2$, where R is the interspin distance. In this model, the points labeled K are associated with a maximally screened Kondo state, whereas M points reflect the existence of magnetic interactions. To show that γ_H is intimately related to J, we compute $2k_F R$ values (top axis) for the shown V_{FG} range (k_F can be estimated directly from n_{2D}, and R has been estimated to be $\sim$1.1 μm from magnetoresistance studies[11]). From the periodicity of π in $2k_F R$ it is clear that the AHE can only probe $|J|$, but the nature (ferromagnetic and/or antiferromagnetic) of the coupling cannot directly be deduced without a detailed temperature dependence. In other words, all M points are equivalent.

However, S_{xy} behaves quite differently. Figure 4(b) shows the evolution of S_{xy} as a function of V_{FG} for $B = 10$ mT. We point out that these variations are much larger in magnitude than the mesoscopic fluctuations discussed earlier. As B is increased, these oscillations reduce in amplitude, until the structure is completely lost at $B = 50$ mT [Figs. 4(c)– 4(e)]. This is consistent with the existence of a delicate spin system that is easily destroyed by relatively small perpendicular magnetic fields.[10] The most striking observation here is that unlike γ_H, S_{xy} displays a periodicity of 2π, which seems to suggest that it actually tracks J, and not $|J|$. The unexpected periodicity of 2π is intriguing, and may potentially allow for a direct determination of the sign of J and hence the nature of the RKKY interaction. To do so unambiguously, it is vital to understand the detailed physical mechanisms that relate J to the transverse TP. The origin of the AHE in GaAs/AlGaAs 2DESs has been attributed to the development of a spontaneous magnetization.[10] In this picture, it is not

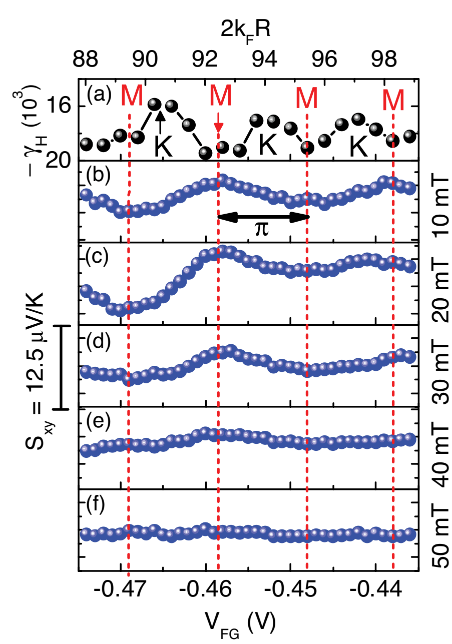

FIG. 4. (Color online) (a) Oscillatory Hall effect. Bottom (top) axis shows the variation of γ_H with V_{FG} ($2k_F R$). K points indicate a Kondo screened state and M points indicate positions where magnetic interactions are significant. Successive K (or M) points are separated by $2k_F R = \pi$. (b) Corresponding variation of S_{xy}, showing a period of 2π in $2k_F R$ at $B = 10$ mT. (c)–(e) Reduction in the amplitude of the oscillations as B is increased further in steps of 10 mT.

immediately clear why the interaction of diffusive electrons with magnetically coupled localized spins (resulting in an anomalous contribution to S_{xy}) would be qualitatively different from ballistic ones (resulting in the AHE). Furthermore, a recent study in dilute magnetic alloys[20] suggests that the AHE and the anomalous Nernst effect actually share the same physical origin, which seems to contradict our results. We suggest that the extreme sensitivity of the Nernst effect on carrier mobility[1] may provide a clue to understanding the observed oscillations in S_{xy}. If we make the assumption that the scattering mechanism (and hence mobility) is highly spin sensitive and thus depends on the strength (and sign) of the RKKY interaction, this might qualitatively account for the observed oscillations in S_{xy}. However, this remains to be put on a stronger theoretical footing. In this regard, an extension of theoretical studies of electronic transport in RKKY coupled quantum dots[21,22] to their magnetothermoelectric properties could perhaps provide insights into the observed anomalous phenomena.

In conclusion, we have investigated the Nernst effect in a mesoscopic 2DES at low B. The magnitude of S_{xy} agrees reasonably well with semiclassical results based on Boltzmann transport theory. In addition to quantum mesoscopic fluctuations, we observe a strong modulation in S_{xy} as the Fermi energy is varied. The observed oscillations indicate that the Nernst effect may potentially be useful in probing magnetic phases in 2DESs. However, to do so efficiently, a further theoretical understanding of the relevant scattering processes is required.

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