

Infrared Hall effect in underdoped and optimally doped LSCO

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We report a study of magneto-optical properties in the mid-infrared region of a series of $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ samples with hole doping level ranging from severely underdoped ($x = 0.03$) to optimally doped ($x = 0.15$). The Faraday rotation and circular dichroism are measured in a magnetic field of 8 Tesla and in a temperature range between 30K and 300K. The doping and temperature dependence of infrared Hall angle is found to be understood within a simple Drude model. A significant increase of Hall frequency is observed when the hole doping level is reduced from optimal doping, which is compared with models of the pseudogap.

As the hole doping in cuprate superconductors is reduced below optimal T_c they enter a pseudogap phase before they ultimately undergo a transition to a Mott insulating ground state. While the pseudogap phase exhibits evidence for a partial gapping of the Fermi surface in many experiments its character is otherwise poorly understood. It is this mysterious pseudogap phase that attracts the greatest attention in the quest for understanding the mechanism for high T_c . Many different scenarios have been proposed for this state [1]. One of the proposals for partially gapping the Fermi surface is the formation of a density wave state. In this scenario the large Fermi surface of the optimally doped system develops energy gaps at the magnetic Brillouin zone boundaries and breaks up into small pockets. However no evidence of energy gaps have been reported from IR studies and the evidence from ARPES is controversial. Recently, Rigal *et.al.* [2] observed a dramatic increase of the Hall frequency in underdoped $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ (YBCO) samples, which is consistent with the presence of Fermi pockets due to a partial gapping of the original Fermi surface. An alternative interpretation of the increase in the Hall frequency follows from recent work by H. Kontani which includes vertex corrections in the calculation of the optical conductivity of the cuprates based on the fluctuation exchange model of the interactions [3, 4]. In any case the analysis of the results in YBCO is complicated by the existence of CuO chains. Therefore it is highly desirable to repeat these magneto-optical studies with other cuprates.

$\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ (LSCO) is an ideal compound to study. It has a relatively simple lattice with one layer of CuO_2 plane, and without the complication of CuO chain as in YBCO. And a wide range of doping level is readily available. Of particular interest is the severely underdoped LSCO, which is predicted by conventional phase diagram of cuprates to be anti-ferromagnetic insulator. However recently angle-resolved photoemission (ARPES) [5], DC transport [6] and Hall effect [7] measurements show evidences of metallic behavior even for $x = 0.02$ sample.

Furthermore, measurement of anisotropy of DC [8] and optical [9] conductivity of de-twinned samples indicates possible existence of charge stripes. In this letter we report the study of magneto-optical properties in the mid-infrared region of a series of LSCO samples ranging from slightly hole doped to optimally doped, by measuring the Faraday rotation and circular dichroism in a magnetic field of 8 Tesla and in a temperature range between 30K and 300K. We found that the doping and temperature dependence of Hall angle can be understood well understood with a simple Drude model. A significant increase of Hall frequency is observed when the hole doping level is reduced from optimal doping, which is consistent with drastic reduction of the volume of Fermi surface in the underdoped sample.

The $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ samples used in this study are severely underdoped ($x = 0.03$), underdoped ($x = 0.10$) and optimally doped ($x = 0.15$) thin films grown on SrTiO_3 substrates by pulsed laser deposition (PLD). The $x = 0.03$ samples does not show superconducting transition, while the other two samples have T_c of 32K and 35K, respectively. The thin films have thickness ranging from 2500 Å to 3800 Å.

In the infrared Hall study various magneto-optical properties such as Hall angle θ_H and Hall conductivity σ_{xy} are obtained by measuring the complex Faraday angle, whose real and imaginary parts correspond to Faraday rotation and circular dichroism when the linearly polarized laser beam from a CO_2 laser pass through the sample. In the mid-infrared region ($900\text{cm}^{-1} \sim 1100\text{cm}^{-1}$) where the measurements are taken, the typical value of Faraday angle is at the order $10^{-4} \sim 10^{-5}$ radians per Tesla. Such a precision measurement of Faraday angle requires a very sensitive technique which is achieved by using a ZnSe photoelastic modulator to analyze the change in the polarization of the laser beam [10].

It has been proved that the optical Hall angle $\tan\theta_H(\omega) \sim \theta_H(\omega) = \sigma_{xy}(\omega)/\sigma(\omega)$ is a response function with its own f -sum rule [11]. Therefore similar to other response function like optical conductivity, the simplest

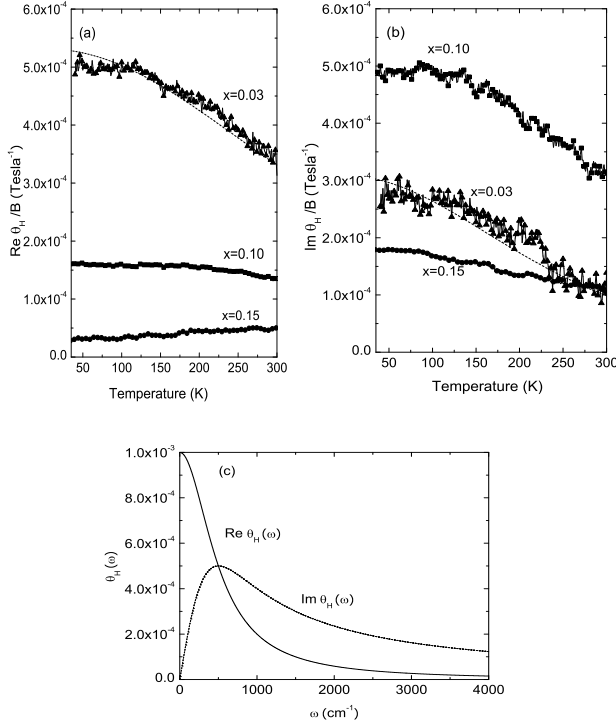


FIG. 1: (a) and (b): Temperature dependence of real (a) and imaginary (b) parts of Hall angle θ_H at $\omega = 1087 \text{cm}^{-1}$ for $x=0.03$, 0.10 and 0.15 samples. (c): Simulated frequency dependence of Hall angle based on simple Drude model with $\gamma_H = 500 \text{cm}^{-1}$, $\omega_H = 0.5$.

functional form of Hall angle is that of the Drude model:

$$\theta_H(\omega) = \frac{\omega_H}{\gamma_H - i\omega}, \quad (1)$$

where the Hall scattering rate γ_H is a different integral [12] of $\gamma(\mathbf{k})$ along the Fermi surface than that of the regular scattering rate, while the Hall frequency ω_H is related to the cyclotron frequency in the simple metal. Study in past few years suggests that the Drude model of Hall angle works well for simple metal films like Au and Cu, as well as hole doped cuprates with various doping, except for electron doped $\text{Pr}_{2-x}\text{Ce}_x\text{CuO}_4$, in which there is evidence of the formation of a spin-density wave state in the underdoped region.

Shown in figure 1(a) and (b) are the temperature dependence of real(a) and imaginary(b) parts of the complex Hall angles θ_H , measured at $\omega = 1087 \text{cm}^{-1}$, for $x = 0.03$, $x = 0.10$ and $x = 0.15$ samples, respectively. When the hole doping level is increased from the severely underdoping level at $x = 0.03$ to the optimally doped level at $x = 0.15$, the real part of θ_H decrease monotonically with increasing doping, while the imaginary part first increases, then decreases with increasing doping. The observed doping dependence of θ_H can be understood if one consult figure 1(c), which is a plot of $\theta_H(\omega)$ based on the simple Drude model (equation 1). Similar

to other more familiar response function like optical conductivity, the real part of $\theta_H(\omega)$ is a Lorentzian centered at $\omega = 0$ with half width γ_H , while the imaginary part reaches its peak at γ_H . Therefore the doping dependence of θ_H can be understood if we assume that γ_H of the $x = 0.03$ sample is larger than $\omega = 1087 \text{cm}^{-1}$ and the other two samples have γ_H smaller than ω .

Plotted in figure 2(a) are the real parts of inverse Hall angles as functions of square of temperature for the three samples, in temperature range from 30K to 300K, as well as their linear fits. Since $\theta_H^{-1} \sim \cot \theta_H$ for small θ_H , it indicates that $\cot \theta_H \propto T^2$ for all three samples, which is consistent with recent result from DC Hall effect [7]. The T^2 linear dependence of $\cot \theta_H$, and therefore the Hall scattering rate γ_H can be demonstrated by fitting the temperature dependence of θ_H by the simple Drude model:

$$\text{Re } \theta_H(T) = \frac{\omega_H \gamma_H(T)}{\gamma_H^2(T) + \omega^2}, \quad \text{Im } \theta_H(T) = \frac{\omega_H \omega}{\gamma_H^2(T) + \omega^2}, \quad (2)$$

with a Hall scattering rate linearly dependent on T^2 : $\gamma_H(T) = a + bT^2$. The dashed lines in figure 1(a) and (b) show such a fit for $x=0.03$ data, with fitting parameters $\omega_H = 1.25 \text{cm}^{-1}$, $a = 1793 \text{cm}^{-1}$ and $b = 1.89 \times 10^{-2} \text{cm}^{-1} \text{K}^{-2}$. This demonstrates that the transport revealed by Hall angle can be well described by a simple Drude model and is similar to that of a conventional Fermi liquid, even for the severely underdoped $x = 0.03$ sample.

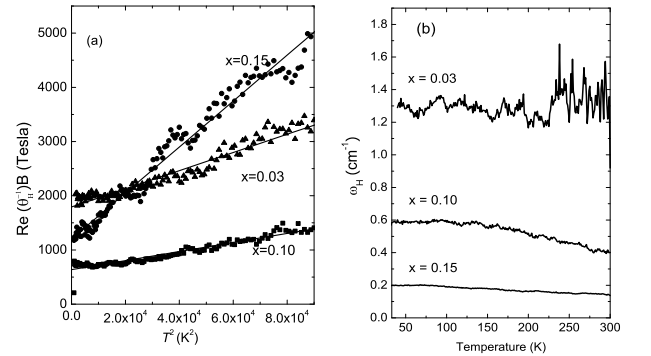


FIG. 2: (a) Real part of inverse Hall angle θ_H^{-1} measured at $\omega = 1087 \text{cm}^{-1}$ for $x = 0.03$, 0.10 and 0.15 samples. (b): Hall frequencies ω_H of the $x=0.03$, 0.10 and 0.15 samples.

Shown in figure 2(b) is the temperature dependence of Hall frequencies ω_H for the three samples obtained from Drude analysis: $\omega_H = -\omega/\text{Im } \theta_H^{-1}$. A weak temperature dependence in ω_H is observed in all three samples. However, drastic increase of ω_H is observed when the hole doping level is reduced, confirming the early observation [2] of similar trend in a set of underdoped YBCO samples. In the case of YBCO, the analysis is complicated by the existence of conducting CuO chains, whose

contribution to optical conductivity is difficult to be reliably subtracted. For a Fermi-liquid the Hall frequency can be expressed in terms of integrals of the Fermi velocity over the Fermi surface as [12]:

$$\omega_H = \frac{eB}{\hbar c} \frac{\oint_{\text{FS}} dS \mathbf{e}_z \cdot \left[\mathbf{v}(\mathbf{k}) \times \frac{d}{dk} \mathbf{v}(\mathbf{k}) \right]}{\oint_{\text{FS}} dS |\mathbf{v}(\mathbf{k})|}. \quad (3)$$

Therefore the observed strong increase in the Hall frequency as the hole doping is reduced from optimal doping suggests that the Fermi surface topography changes significantly. One possible scenario is the gapping out of part of Fermi surface in underdoped samples by the formation of a density wave state. In case of underdoped LSCO, there is evidence from ARPES [5] suggesting that, for severely underdoped $x = 0.03$ sample, a significant fraction of the large Fermi surface which is observed in optimally doped samples is destroyed and the remaining small portion is a small pocket near $(0.42\pi, 0.42\pi)$. The observed increase in Hall frequency in the density wave state is predicted by a calculation [15] within the d -density wave (DDW) model using the semiclassical Boltzmann theory in the weak field limit [16]. However, there is an alternative interpretation in terms of the effects of interactions on the optical magneto-conductivity. Recent work by Kontani [4] based on the fluctuation exchange model in which vertex corrections are included in the calculation of the Hall conductivity also shows a Drude like response of the Hall angle and an increase of ω_H by 70% when doping level is reduced from $x = 0.20$ to $x = 0.10$. In choosing between these two interpretations it is noteworthy that evidence for a density wave gap has not been reported for the hole doped cuprates. By contrast $\text{Pr}_{2-x}\text{Ce}_x\text{CuO}_4$, an electron doped cuprate, which exhibits a gap like feature in σ_{xx} , displays a different σ_{xy} response than the hole doped cuprates in which features associated with density wave gap excitations are seen [17, 18].

In summary, we studied the infrared Hall effect in a series of LSCO samples with the hole doping level ranging from severely underdoped ($x = 0.03$) to optimally doped ($x = 0.15$). We found that the doping and temperature dependence of Hall angle can be well described with a simple Drude model. A significant increase of the Hall frequency is observed when the hole doping level is reduced from optimal doping. This finding can be ascribed to either a drastic reduction of the volume of Fermi surface in the underdoped sample due to the formation of a

density wave state or to the effects of vertex corrections on the Hall conductivity in a strongly interacting electron system. The absence of evidence for a density wave gap in the σ_{xx} , and σ_{xy} spectra of LSCO indicates that the second interpretation is the correct one.

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