# High magnetic field sensor using $LaSb_2$

D. P. Young, R. G. Goodrich, J. F. DiTusa, S. Guo, and P. W. Adams[a)]
*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana, 70803*

Julia Y. Chan
*Department of Chemistry, Louisiana State University, Baton Rouge, Louisiana, 70803*

Donavan Hall[b)]
*National High Magnetic Field Laboratory, Florida State University, Tallahassee, Florida, 32306*

(Received 20 January 2003; accepted 31 March 2003)

The magnetotransport properties of single crystals of the highly anisotropic layered metal $LaSb_2$ are reported in magnetic fields up to 45 T with fields oriented both parallel and perpendicular to the layers. Below 10 K the perpendicular magnetoresistance of $LaSb_2$ becomes temperature independent and is characterized by a 100-fold linear increase in resistance between 0 and 45 T with no evidence of quantum oscillations down to 50 mK. The Hall resistivity is hole-like and gives a high field carrier density of $n \sim 3 \times 10^{20}\ \mathrm{cm}^{-3}$. The feasibility of using $LaSb_2$ for magnetic field sensors is discussed. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1577390]

One of the most successful strategies for producing technologically relevant magnetoresistive materials is to enhance the effects of field-dependent magnetic scattering processes through the creation of magnetic superlattices[1] or by doping magnetic insulators such that a magnetic and metal–insulator transition coincide.[2] Unexpectedly, there have been several recent discoveries of a large, nonsaturating magnetoresistance (MR) in low carrier density nonmagnetic metals[3–7] and semiconductors.[8] One class of these systems, the slightly off-stoichiometric silver chalcogenides, $Ag_{2+\delta}Te$ and $Ag_{2+\delta}Se$, has shown significant promise as the basis of ultrahigh magnetic field sensors by virtue of the fact that they exhibit a multifold, quasilinear MR that remains unsaturated up to 60 T.[8] In this letter we present magnetotransport data on the highly layered nonmagnetic metal $LaSb_2$ which displays a 100-fold, linear MR with no sign of saturation up to 45 T. We show that in many respects, including sensitivity, linearity, synthesis characteristics, and intrinsic anisotropy, $LaSb_2$ is a compelling candidate for high-field sensor development.

$LaSb_2$ is a member of the $RSb_2$ (R=La-Nd,Sm) family of compounds that all form in the orthorhombic $SmSb_2$ structure.[9,10] $LaSb_2$, in particular, is comprised of alternating La/Sb layers and two-dimensional rectangular sheets of Sb atoms stacked along the $c$ axis.[11] Similar structural characteristics give rise to the anisotropic physical properties observed in all the compounds in the $RSb_2$ series.[12] Since $LaSb_2$ is nonmagnetic, its low-temperature transport properties are not complicated by magnetic phase transitions which occur in the other members of this series.[12]

Single crystals of $LaSb_2$ were grown from high purity La and Sb by the metallic flux method.[13] The orthorhombic $SmSb_2$-structure type was confirmed by single crystal x-ray diffraction. The crystals grow as large flat layered plates which are malleable and easily cleaved. Typically flux grown samples had dimensions of 5 mm×5 mm×0.2 mm. Electrical contact was made using Epotek[14] silver epoxy and 1 mil gold wire. Transport properties were measured using a 27 Hz four-probe ac technique at temperatures from 0.03 to 300 K and in magnetic fields up to 45 T. In all of the measurements presented probe currents of 1–5 mA were used with corresponding power levels less than 10 nW. Hall effect measurements were made on natural thickness samples in a four-wire geometry with data being taken in both positive and negative fields up to 30 T.

The in-plane zero-field electrical resistivity, $\rho$, of single crystals of $LaSb_2$ was measured from 1.8 to 300 K and found to be metallic $(d\rho/dT>0)$. The residual resistivity ratio was large $[\rho_{ab}(300\ \mathrm{K})/\rho_{ab}(2\ \mathrm{K})\approx 70–90]$, indicating a high sample quality. In the main panel of Fig. 1 we show the transverse MR with the field oriented parallel and perpen-

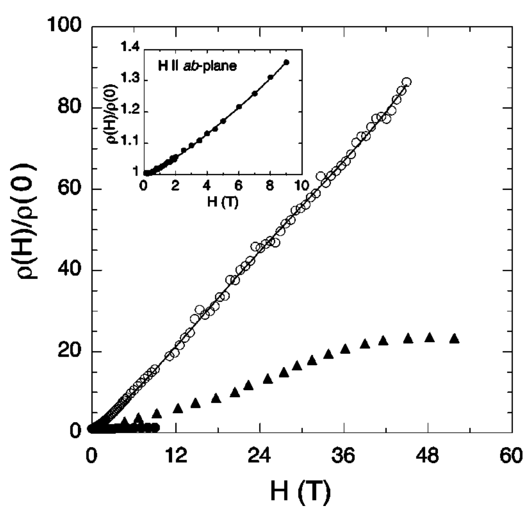


FIG. 1. Transverse MR of $LaSb_2$ at $T=2$ K with the current in the $ab$ plane and magnetic field oriented parallel (closed circles) and perpendicular (open circles) to the $ab$ plane. The solid triangles represent the MR of $Ag_{2+\delta}Se$ as taken from Ref. 8. Inset: Low field MR with $H\|ab$ plane. The solid lines represent a least-squares fit to the data using a fourth-order polynomial (Table I).

a)Electronic mail: adams@rouge.phys.lsu.edu
b)Present address: American Physical Society, One Research Road, Box 9000, Ridge, NY 11961.

 

TABLE I. Polynomial coefficients obtained from a least squares fit to the data in Figs. 1–3 using a fourth-order polynomial, $f(H)=\alpha_0+\alpha_1 H+\alpha_2 H^2+\alpha_3 H^2+\alpha_4 H^4$.

| | $\alpha_0$ | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\alpha_4$ |
|---|---|---|---|---|---|
| $\rho(H)/\rho(0)$ $(H\parallel\hat{c})$ | 1 | 1.236 | 0.0579 | $-1.874\times10^{-3}$ | $2.019\times10^{-5}$ |
| $\rho(H)/\rho(0)$ $(H\perp\hat{c})$ | 1 | 0.0182 | $5.601\times10^{-3}$ | $-6.260\times10^{-4}$ | $3.032\times10^{-5}$ |
| $\rho(H_\perp)/\rho(0)$ $(H=9\text{T})$ | 1 | 0.3315 | 0.1023 | $4.598\times10^{-3}$ | $-7.931\times10^{-4}$ |
| $\rho(H_\perp)/\rho(0)$ $(H=4.5\text{T})$ | 1 | 0.4624 | 0.0827 | 0.04644 | $-6.775\times10^{-3}$ |
| $\rho_{xy}(H)$ $(\mu\Omega\text{-cm})$ | 0 | 0.0225 | 0.1781 | $-4.309\times10^{-3}$ | $3.757\times10^{-5}$ |

dicular to the *ab* plane. Both MRs are positive and nearly linear above 2 T. Note the extreme anisotropy in the magnetotransport with the perpendicular MR being an order of magnitude larger than the parallel MR. The perpendicular MR was large, with resistance increasing by a factor of 90 from 0 to 45 T. The MR was temperature independent below 10 K but decreased rapidly above 30 K. Interestingly, there is no evidence of saturation or quantum oscillations in the MR of Fig. 1 which has obvious advantages for magnetic field sensor applications. The solid lines in Fig. 1 are least-square fits to a fourth-order polynomial (Table I). Note the high quality of the fits to the MR using this simple functional form. The relative field sensitivity, which is the figure of merit for a sensor, is represnted by $\alpha_1=1.23\ \text{T}^{-1}$. This sensitivity is roughly a factor of 4 greater than that of $Ag_{2+\delta}Se$ (triangle symbols in Fig. 1).

The anisotropy of the MR can be demonstrated by measuring the transverse MR as a function of the tilt angle in a constant magnetic field. In Fig. 2 we plot the resistivity normalized by the parallel field value, $\rho(H_\perp=0)$, as a function of the perpendicular component of the field $H_\perp$. Interestingly, the general shape of the MR curves in Fig. 2 is quite similar to those of Fig. 1. The solid lines are polynomial fits to the data (Table I). In terms of a magnetic field sensor, this anisotropy can be exploited to determine the angle of orientation in tilted field studies. The micaceous nature of $LaSb_2$ not only produces an anisotropic MR but also presents a convenient geometry for Hall measurements, namely large flat crystals. In the main panel of Fig. 3 we plot the Hall resistivity, $\rho_{xy}$, as a function of magnetic field at $T=2$ K. In the right inset of Fig. 3 we show the low field behavior of $\rho_{xy}$ which is negative below 0.5 T but becomes positive at higher fields. This latter behavior is often characteristic of a two-carrier system.[15] In the high field limit the majority carrier dominates, which in our case is hole-like. Above 10 T the Hall constant is $R_H\sim2\times10^{-6}\ \mu\Omega$ cm/T which corresponds to a carrier density of $n\sim3\times10^{20}\ \text{cm}^{-3}$ and a Hall mobility $\mu\sim0.05\ \text{m}^2/\text{V s}$. We note that the overall shape of the Hall resistance curve in the right inset of Fig. 3, with its local minimum, is very similar in character to that of $NbSe_2$ and $TaSe_2$ which also form in nonmagnetic micaceous crystalline structures.[16]

A useful measure of the magnitude of the linear MR is the dimensionless Kohler slope, $S=(1/R_H)[d\rho(H)/dH]$. Combining the Hall constant measurements with the value of $\alpha_1$, obtained from the MR of Fig. 1, we get a high field value $S\sim0.6$. This value is an order of magnitude larger than what is typical of other nonmagnetic systems displaying a linear MR. Classically, the MR should vary quadratically with field. In a closed orbit system the MR saturates in the high field limit, $\omega_c\tau\gg1$, where $\omega_c$ is the cyclotron frequency and $\tau$ is the elastic scattering time.[15] Over the past 30 years several mechanisms have been proposed to account for anomalous linear MR observed in a wide variety nonmagnetic systems such as elemental metals,[5,17] two-dimensional heterostructures,[18] and disordered semiconductors.[8] Theories accounting for linear MR fall into two main categories. The first contains theories associated with the alteration of the structural symmetry due to the formation of a charge density

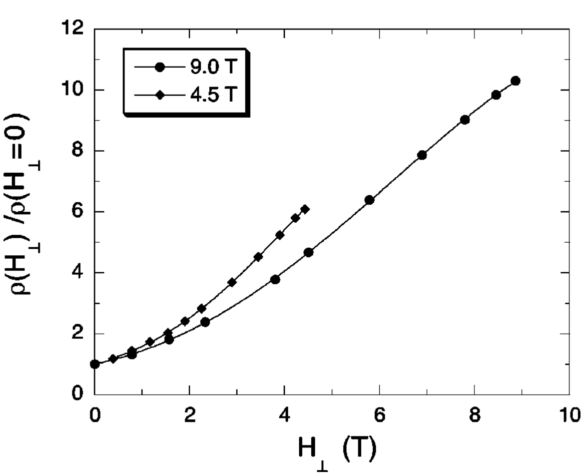


FIG. 2. MR in a tilted magnetic field. The samples were rotated out of the $H\parallel ab$ plane in constant magnetic fields of 9.0 and 4.5 T. The MR at 2 K is plotted as a function of the perpendicular component of the field. The solid lines represent a least-squares fit to the data using a fourth-order polynomial (Table I).

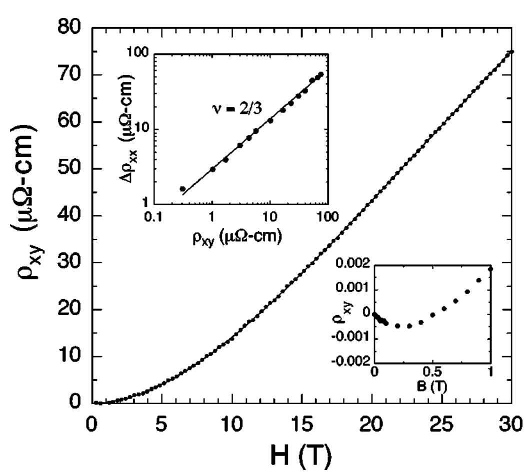


FIG. 3. Transverse MR of $LaSb_2$ at $T=2$ K with the current in the *ab* plane and magnetic field oriented parallel (closed circles) and perpendicular (open circles) to the *ab* plane. The solid triangles represent the MR of $Ag_{2+\delta}Se$ as taken from Ref. 8. Inset: Low field MR with $H\parallel ab$ plane. The solid lines represent a least-squares fit to the data using a fourth-order polynomial (Table I).

wave (CDW).[19] Linear MR in very pure elemental metals has been attributed to quantum fluctuations about a CDW ground state[20] and/or a magnetic breakdown of the CDW gap.[15,21] The second includes theories which invoke high field quantization effects or singular scattering mechanisms which cannot be accounted for by the standard perturbative scattering formulations.[3,22] Interestingly, the transition metal dichalogenides $NbSe_2$ and $TaSe_2$ both have well established CDW ground states and exhibit an anomalous linear MR. These compounds are similar in structure to $LaSb_2$, suggesting that perhaps a CDW state plays a central role in the MR of $LaSb_2$. At this time, however, is not known whether $LaSb_2$ undergoes a charged density wave transition.

It has been known for many years that the relative MR, $\Delta\rho/\rho$, of many metals and semimetals is a temperature independent function of magnetic field.[23] In particular, $\Delta\rho/\rho = F(H)$, where $F(H)$ usually has a power-law form. $LaSb_2$ is known to obey this rule, commonly refered to as Kohler's rule, with $F(H) \sim H$.[12] One can also make a similar analysis by substituting the the Hall resistance for the magnetic field $H$. The resulting modified Kohler plot for $LaSb_2$ is shown in the left inset of Fig. 3. The solid line in the plot has a slope of $\nu = 2/3$ indicating that $\Delta\rho \propto \rho_{xy}{}^{2/3}$. Interesingly, $Ag_{2+\delta}Se$ also exhibits power-law behavior but with a low temperature modified Kohler slope of $\nu = 5/3$.[8] This suggests that the underlying MR mechanisms in these two seemingly unrelated systems may be similar and that the differing scaling exponents is a dimensionality effect.

In conclusion, we show that crystalline $LaSb_2$ is an attractive material for use as a high magnetic field sensor. It is relatively easy to synthesize, and electrical contact can be made with silver epoxy. By virtue of its highly anisotropic structure, $LaSb_2$ can be used in either a transverse MR configuration or a Hall configuration. The sensitivity in both configurations is quite good. Calibration curves for both the MR and the Hall resistance can be made using a fourth-order polynomial, thus avoiding numerical difficulties associated with complicated fitting forms.

The authors gratefully acknowledge discussions with Dana Browne and Richard Kurtz. This work was supported by the National Science Foundation under Grant Nos. DMR 99-72151 and DMR 01-03892. They also acknowledge support of the Louisiana Education Quality Support Fund under Grant No. 2001-04-RD-A-11. A portion of this work was performed at the National High Magnetic Field Laboratory, which is supported by NSF Cooperative Agreement No. DMR-9527035 and by the State of Florida.

[1] M. N. Baibich, J. M. Broto, A. Fert, F. N. Vandau, F. Petroff, P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas, Phys. Rev. Lett. **61**, 2472 (1988); R. E. Camlery and R. L. Stamps, J. Phys.: Condens. Matter **5**, 3727 (1993).
[2] S. Jin, T. H. Tiefel, M. McCormack M, R. A. Fastnacht, R. Ramesh, and L. H. Chen, Science (Washington, DC, U.S.) **264**, 413 (1994).
[3] A. A. Abrikosov, Phys. Rev. B **60**, 4231 (1999); A. A. Abrikosov, Europhys. Lett. **49**, 789 (2000).
[4] I. M. Lifshits and V. G. Peshanskii, Sov. Phys. JETP **8**, 875 (1959).
[5] L. M. Falicov and H. Smith, Phys. Rev. Lett. **29**, 124 (1972).
[6] D. E. Soule, Phys. Rev. **112**, 698 (1958); J. W. McClure and W. J. Spry, *ibid.* **165**, 809 (1968).
[7] In this case a multifold positive, linear, magnetoconductance is seen, V. Yu. Butko, J. F. Ditusa, and P. W. Adams, Phys. Rev. Lett. **85**, 162 (2000); V. Yu. Butko and P. W. Adams, Nature (London) **409**, 161 (2001).
[8] A. Husmann, J. B. Betts, G. S. Boebinger, A. Migliori, T. F. Rosenbaum, and L. Saboungi, Nature (London) **417**, 421 (2002).
[9] R. Wang and H. Steinfink, Inorg. Chem. **6**, 1685 (1967).
[10] F. Hullinger, in *Handbook of Physics and Chemistry of Rare Earths*, edited by K. A. Gschneidner and L. Eyring (North-Holland, Amsterdam, 1979), Vol. 4, p. 153.
[11] X-ray analysis determined the lattice constants to be 0.6319, 0.6173, and 1.857 nm for the $a$, $b$, and $c$ crystallographic directions, respectively.
[12] S. L. Bud'ko, P. C. Canfield, C. H. Mielke, and A. H. Lacerda, Phys. Rev. B **57**, 13624 (1998).
[13] P. C. Canfield and Z. Fisk, Philos. Mag. B **65**, 1117 (1992).
[14] Epoxy Technology, 14 Fortune Dr., Billerica, MA, 01821 (www.epotek.com).
[15] N. W. Ashcroft and N. D. Mermin, *Solid State Physics* (Saunders, New York, 1976).
[16] M. Naito and S. Tanaka, J. Phys. Soc. Jpn. **51**, 228 (1982).
[17] P. L. Kapitza, Proc. R. Soc. London, Ser. A **119**, 358 (1928).
[18] H. L. Stormer, K. W. West, L. N. Pfeiffer, and K. W. West, Solid State Commun. **84**, 95 (1992).
[19] A. W. Overhauser, Phys. Rev. B **3**, 3173 (1971).
[20] A. H. C. Neto, Phys. Rev. Lett. **86**, 4382 (2001).
[21] J. A. Wilson, F. J. DiSalvo, and S. Mahajan, Adv. Phys. **24**, 117 (1975).
[22] R. A. Young, Phys. Rev. **175**, 813 (1968).
[23] A. A. Abrikosov, *Fundamentals of the Theory of Metals* (North-Holland, Amsterdam, 1988).