APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 3 21 JULY 2003

Electrical noise in *n*- and *p*-type Ag_2Te

L. Jiang and E. R. Nowak[a)]
Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716

(Received 6 January 2003; accepted 21 May 2003)

The relatively large and linear magnetoresistance found in nonstoichiometric silver chalcogenides makes them attractive candidates for field sensing applications. We report on the intrinsic electrical noise in bulk, polycrystalline $Ag_{2+\delta}Te$. Low-frequency noise is due to resistance fluctuations having a $1/f$-like power spectrum. The temperature dependence of the noise magnitude and its spectral slope indicate thermally activated kinetics that we attribute to some form of charge trapping–detrapping process occurring in or near the intergranular regions. The effective magnetic field noise in $Ag_{2+\delta}Te$ is compared to other materials systems used in field sensing applications. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1593820]

Silver telluride is a member of the silver chalcogenide family of nonmagnetic, narrow-band-gap semiconductors. Although the stoichiometric material (β-Ag_2Te) exhibits no appreciable magnetoresistance (MR),[1,2] large magnetoresistive effects have been reported for small deviations from stoichiometry.[3] These effects include resistance increases of up to 200% at room temperature and in a magnetic field of ~50 kOe. The magnetic response found in Ag-rich material is surprisingly linear, down to a few Oersteds, making it an attractive candidate for low-field applications. Te-rich material seems most suitable for high-field applications, maintaining a high-field MR that is sizeable even at room temperature and does not saturate at magnetic fields much larger than the cyclotron scale.[4] Recent pressure-dependence studies have highlighted the importance of carrier density to the MR; maximal MR and minimal onset field for linearity were observed at perfect compensation.[5] For technological prospects, the detection sensitivity to resistance changes will be limited by the intrinsic noise of the material. Characterizing this noise and identifying its origin is thus particularly relevant to making materials with optimal properties for magnetic field sensing applications.

Bulk, polycrystalline samples of silver rich (*n*-type) and silver deficient (*p*-type) β-$Ag_{2+\delta}Te$ material were made by a melt-doping process, as described in Ref. 4. The stoichiometric index δ, of these samples ranged from -0.0005 to 0.0009. We cut specimens with typical dimensions of 1 mm wide and 2 mm long, and then mechanically polished them to a thickness of approximately 0.2 mm. Wire leads were ultrasonically soldered to each corner of the specimen. A low-melting-point indium alloy solder was used to prevent heating the specimen above 400 K and into its high temperature (α) phase.[2] Four-probe resistance and noise measurements were performed in applied magnetic fields up to 5 kOe, oriented perpendicular to the direction of the current. Due to the finite extent of the In pads, there can be up to 50% error in the absolute value of the resistance.

The normalized MR, $\Delta\rho/\rho$, for a *n*-type sample having $\delta = 0.0009$ is shown in the inset of Fig. 1. $\Delta\rho/\rho(H = 5\ \mathrm{kOe})$ is ~2% at room temperature, but it increases appreciably upon cooling, reaching ~17% at 15 K. The linear dependence of $\Delta\rho/\rho$ on H is most pronounced at low temperatures and for fields above approximately 1 kOe. Since our samples are close to stoichiometry, the observed MR is smaller and the onset of linearity is at higher fields compared to previous reports[3] on samples with $\delta \sim 0.01$.

The temperature dependence of the resistivity $\rho(T)$ reflects the behavior of a narrow-gap semiconductor. $\rho(T)$ is plotted in Fig. 1 for a series of nominal dopings $\delta = -0.0005$, 0, 0.0005, and 0.0009. The corresponding carrier density was determined from the Hall coefficient R_H, measured in the extrinsic regime at 5 K; R_H is 25, 200, 100, and 5 cm^3/C, respectively. In the extrinsic regime ($T < 60$ K for these samples), the resistivity is nearly independent of temperature because effective carrier density is constant.[3] At higher T, the transport becomes activated and the resistivity decreases with increasing T as expected in the intrinsic regime. In addition, as the material is made more silver rich ($\delta > 0$) its resistivity decreases.

Noise measurements were performed under constant current conditions by using a battery and a ballast resistor. The power spectral density S_V of the voltage fluctuations across

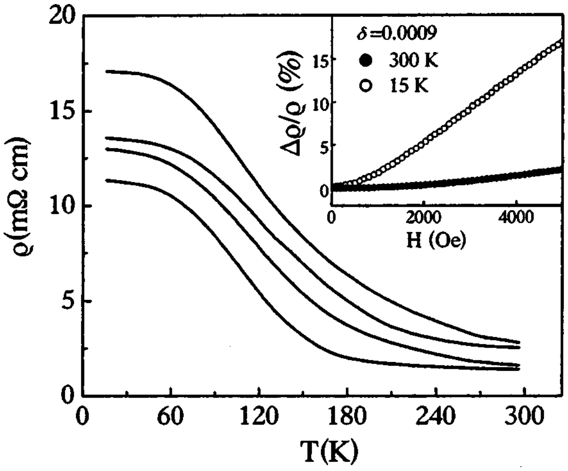

FIG. 1. The temperature dependence of the resistivity, $\varrho(H=0)$, in $Ag_{2+\delta}Te$ is shown for various stoichiometries; from top to bottom, $\delta = -0.0005$, 0, 0.0005, and 0.0009. The inset shows typical MR curves. The field was applied perpendicular to the direction of the current.

[a)] Electronic mail: nowak@udel.edu

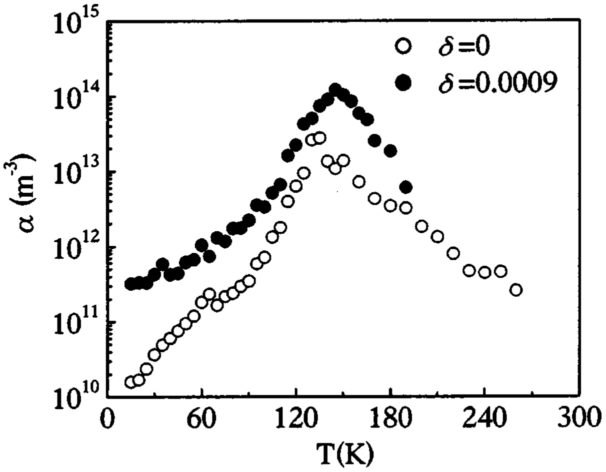

FIG. 2. Shown is the temperature dependence of the $1/f$ noise parameter α at 50 Hz. All samples showed nonmonotonic behavior with a distinct peak near 135 K.

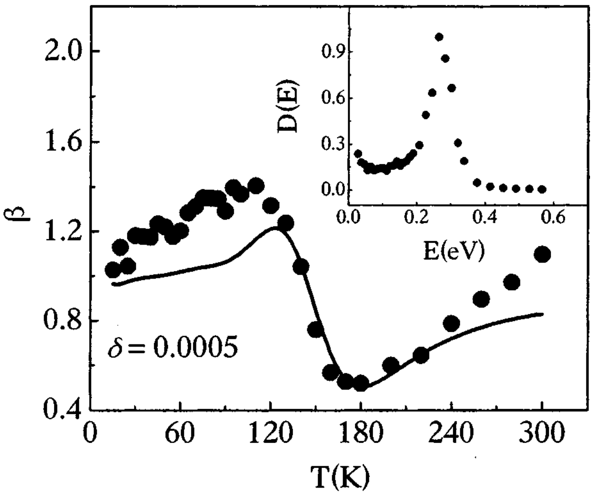

FIG. 3. The temperature dependence of the measured spectral slope, β, is plotted along with the DDH prediction (solid line), see Eq. (1). The inset shows the distribution of activation energies responsible for the temperature dependences of the noise magnitude and its spectral slope.

the sample scales approximately as I^2/f^β, where I is the dc current and f is frequency. The spectral exponent β ranges between 0.6 and 1.4 and is temperature dependent. Measurements of a sample's intrinsic noise were generally restricted to frequencies less than a few kilohertz due to a combination of factors, including large-sample volumes, self-heating due to contact resistance, and amplifier noise. We expect the noise spectrum to crossover from $1/f$-like to frequency-independent behavior at higher frequencies due to either Johnson noise or carrier recombination noise.[6]

We parameterize the noise magnitude of specimens that exhibit a $1/f$-like power spectrum by defining a phenomenological parameter $\alpha \equiv (fnS_V)/I^2R^2$, where R is resistance and n is the carrier density.[7,8] n was determined from the low-temperature Hall coefficient data. The temperature dependence of the noise, $\alpha(T)$, is plotted in Fig. 2. $\alpha(T)$ is nonmonotonic, exhibiting a maximum in the intrinsic regime at a temperature (~135 K) that depends somewhat on the value of δ. The noise magnitude decreases rapidly on either side of the maximum; for some samples, α drops by a factor of 1000 over our temperature range. At high temperatures, the resistance of the samples is sufficiently low such that we were unable to resolve the $1/f$ noise near room temperature. Although the nonmonotonic behavior of $\alpha(T)$ emerges as a general feature of all the samples, variations in the magnitude of α from sample to sample for fixed δ can be large (a factor of 3 is typical). Taking this variance into account, the nonstoichiometric samples ($\delta \neq 0$) have nominally the same values of α and are on average somewhat noisier than the stoichiometric compound.

$1/f$ noise in semiconductors is generally attributed to some form of charge trapping–detrapping.[8] In Ag_2Te, the $1/f$ noise magnitude (S_V) does not scale as $(d\varrho/dT)^2$, ruling out an alternative mechanism based on a simple temperature fluctuation model.[9] The nonmonotonic form of $\alpha(T)$ and the $1/f$-like spectrum are consistent with a Dutta, Dimon, and Horn (DDH) picture for $1/f$ noise.[10,11] For thermally activated fluctuations in trap occupation, the spectrum around some frequency f at any temperature T comes mainly from sites having thermal activation energies $E \approx k_BT\ln(f_0/f)$, where $f_0 \sim 10^{12}$ Hz is an attempt frequency on the order of the phonon frequency. If the spectral shape results from a broad, but not arbitrarily broad, distribution of E, then the spectral exponent is not quite 1 and, under some realistic conditions,[10,11] should be related to the temperature dependence of the spectral density itself in the following way:

$$\beta = -\frac{\partial \ln S(f,T)}{\partial \ln f} = 1 + \frac{1}{\ln(f_0/f)}\left[\frac{\partial \ln S(f,T)}{\partial \ln T} - 1\right]. \quad (1)$$

Here, $S(f,T) = S_\varrho(f,T)/\varrho^2(T)$ in order to factor out the temperature dependence of the resistivity. The predicted DDH spectral slope and the measured slope are in qualitative agreement, as is demonstrated for a Ag-rich sample in Fig. 3. These results indicate that the kinetics of the $1/f$ noise mechanism are thermally activated. The inset of Fig. 3 shows the corresponding distribution of activation energies, $D(E) \propto \omega S_V/V^2k_BT$, which is peaked at ~260 meV and has a width of 50 to 100 meV. This activation energy is larger than the semiconducting gap in Ag_2Te, which is only 120 meV.

The linear MR in nonstoichiometric silver chalcogenides is believed to require an inhomogeneous medium with highly conducting regions, due, for example, to excess silver forming metallic clusters embedded in less conducting material.[5,12,13] Disorder, in the form of spatial fluctuations in conductivity, can lead to broad distributions of energy scales and time scales. If conductivity fluctuations are sufficiently large, distorted current paths may give rise to non-Gaussian noise power fluctuations;[8] however, such behavior was not observed in these samples. We speculate that the disorder is uniform on a macroscopic scale and that the broadband noise spectra in $Ag_{2+\delta}Te$ are due to charge traps located near the interfaces between highly and poorly conducting regions of the material.

Using the low-temperature magnetoresistance and noise data for a sample having $\delta = 0.0005$, we estimate that $1/f$ resistance fluctuations lead to an effective magnetic field noise of 50 mOe/$\sqrt{\text{Hz}}$ at 50 Hz. This is a factor of 10^4 higher than the noise of field sensors[14] based on giant magnetoresistive materials or spin-polarized tunnel junctions.[15] Hence, the near stoichiometric ($\delta \approx 0$) silver chalcogenides may not compare favorably for low-field, low-frequency applications. However, magnetic field sensors based on Ag_2Te and Ag_2Se do have a niche in pulsed magnet applications that involve high fields and higher frequencies.[16] Other devices would likely make use of thin films of silver chalcogenide[17] that may have considerably different noise properties.

One of the authors (E.R.N.) is grateful to H. S. Schnyders and M. Lee for preparing the samples, and to T. F. Rosenbaum and M.-L. Saboungi for illuminating discussions. This work was supported in part by the University of Delaware Research Foundation, the Donors of The Petroleum Research Fund, administered by the American Chemical Society, and by the National Science Foundation.

[1] P. Junod, Helv. Phys. Acta **32**, 567 (1959).
[2] P. Junod, H. Heidiger, B. Kilchor, and J. Wullschleger, Philos. Mag. **36**, 941 (1977).
[3] R. Xu, A. Husmann, T. F. Rosenbaum, M.-L. Saboungi, J. E. Enderby, and P. B. Littlewood, Nature (London) **390**, 57 (1997).
[4] H. S. Schyders, M.-L. Saboungi, and T. F. Rosenbaum, Appl. Phys. Lett. **76**, 1710 (2000).
[5] M. Lee, T. F. Rosenbaum, M.-L. Saboungi, and H. S. Schnyders, Phys. Rev. Lett. **88**, 066602 (2001).
[6] K. M. van Vliet and J. R. Fasset, in *Fluctuation Phenomena in Solids*, edited by R. Burgess (Academic, New York, 1965),p. 294.
[7] F. N. Hooge, Physica B **83**, 14 (1976).
[8] M. B. Weissman, Rev. Mod. Phys. **60**, 537 (1988).
[9] M. B. Ketchen and J. Clarke, Phys. Rev. B **17**, 114 (1978).
[10] P. Dutta, P. Dimon, and P. M. Horn, Phys. Rev. Lett. **43**, 646 (1979).
[11] P. Dutta and P. M. Horn, Rev. Mod. Phys. **53**, 497 (1981).
[12] A. A. Abrikosov, Phys. Rev. B **58**, 2788 (1998).
[13] A. A. Abrikosov, Europhys. Lett. **49**, 789 (2000).
[14] M. Tondra, J. M. Daughton, C. Nordman, D. Wang, and J. Taylor, J. Appl. Phys. **87**, 4679 (2000).
[15] G. A. Prinz, Science **282**, 1660 (1998).
[16] A. Husmann, J. B. Betts, G. S. Boebinger, A. Migliori, T. F. Rosenbaum, and M.-L. Saboungi, Nature (London) **417**, 421 (2002).
[17] I. S. Chuprakov and K. H. Dahmen, Appl. Phys. Lett. **72**, 2165 (1998).