Anisotropic pseudogap in CeNiSn and CeRhSb studied by a thermal-conductivity measurement

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We have measured the thermal conductivity κ for CeNiSn, $CeNi_{0.95}M_{0.05}Sn$ (M=Co,Cu), and CeRhSb single crystals. The pronounced enhancement of κ along the b axis is observed around 5 and 10 K in CeNiSn and CeRhSb, respectively. In CeNiSn, this enhancement is almost completely suppressed either by application of a magnetic field of 15 T along the a axis, which is the easy axis of magnetization, or by the substitution of 5% Co and Cu for Ni. These results indicate that the enhancement of κ along the b axis originates from the opening of the pseudogap in these compounds. On the other hand, the enhancement of κ along the a axis in CeNiSn and those along the a and c axis in CeRhSb are much smaller than that along the b axis. These anisotropic behaviors in κ reflect the anisotropy of the gap in these compounds. [S0163-1829(97)05510-0]

I. INTRODUCTION

In recent years, the Kondo insulator has attracted much attention both experimentally and theoretically. It is well known that a gap is opened in the electronic density of states in SmB_6,[1] YbB_{12},[2] and TmSe,[3] etc., at low temperatures. In Ce compounds, while most of those have a metallic ground state, few compounds, CeNiSn,[4] CeRhSb,[5,6] and $Ce_3Bi_4Pt_3$ (Ref. 7) belong to such a category. Among them, CeNiSn has been extensively studied because of the much smaller magnitude of the gap than the others. The results of NMR,[8] specific heat,[9] tunneling spectroscopy,[10] etc., showed that the density of states at the Fermi energy, $N(\varepsilon_F)$, decreases strongly below ~10 K, which was ascribed to the opening of the pseudogap. The nuclear spin-lattice relaxation rate T_T^{-1} proportional to T^3 below ~10 K suggests that a pseudogap with a V-shaped structure opens at low temperatures.[8] We define the temperature below which the pseudogap is opened as T_{Gap}. The mechanism of the anisotropic pseudogap formation was proposed by Ikeda and Miyake.[11] The gap can be easily destroyed by external forces such as the magnetic field along the easy a axis of magnetization,[12] pressure,[13] or a small amount of substitution.[14] The negative magnetoresistance is largest for the $B\|a$ axis and smallest for the $B\|c$ axis.[12] The same tendency has been observed in the specific heat[12] and thermoelectric power[15] under the magnetic field. These were explained as a result of the pseudogap's being destroyed by the magnetic field, and the pseudogap is most easily destroyed for $B\|a$ and most difficult to be destroyed for $B\|c$. The a axis is the easy axis of magnetization M and the c axis is the difficult axis of M.[9] Thus, the degree of destruction of the pseudogap depends on the applied field direction. The quality of the samples at the early stage was not good, and the electrical resistivity showed semiconductive behavior at low temperatures.[4] However, now the sample quality becomes much better because of the progress of the sample preparation and purification.[16] The isostructural CeRhSb also belongs to the category of the Kondo insulator and has also been extensively studied.[5,6] The results of the specific heat[6] and NMR,[17] etc., suggest that the pseudogap opens below ~20 K, and the magnitude of the gap is about twice as large as that in CeNiSn. Due to the larger magnitude of the pseudogap, stronger external forces are necessary.[18–20]

Isikawa *et al.* first reported the thermal conductivity κ of the CeNiSn single crystal.[21] Along the b axis, κ shows the minimum and the maximum at ~6 and ~5 K, respectively. It was argued that the maximum of κ originates from the enhancement of the phonon relaxation time τ_{oh} because of the gap opening, in analogy with the mechanism proposed for the enhancement of κ below T_c in the high-T_c cuprates by Uher and Kaiser.[22] It was considered that heat current is carried mainly by phonons in a wide temperature region and phonons are scattered by conduction electrons at high temperatures, but τ_{ph} increases as a result of the strong decrease in the number of conduction electrons below the gap formation temperature. Hiess *et al.* measured κ in a low-temperature region between ~0.1 and 6 K and concluded that κ is dominated by phonons at low temperatures.[15] The electrical resistivity of the sample used by Isikawa *et al.* showed semiconducting behavior at low temperatures. However, the sample quality has become much better at present,[16] and therefore the temperature dependence of κ should be reexamined by using a sample of better quality.

One of the purposes of the present work is to study the thermal conductivity of a better quality sample in a wide temperature region up to 100 K. It is also important to compare the thermal conductivity of CeNiSn with those of another Kondo semiconductor, CeRhSb, and Kondo metal CePtSn, and to extract what is the common behavior in κ associated with the existence of the gap.

The gap in CeNiSn is suppressed by applying the high

magnetic field along the a axis, but is little affected by the magnetic field along the c axis, as mentioned above. If the anomaly of κ along the b axis originates from the opening of the gap,[21] it should be affected largely by the magnetic field along the a axis. The second purpose is to study how κ of CeNiSn varies under the magnetic field up to 15 T. The results of NMR show that the gap is easily suppressed by the Ni site substitution.[14] This prompted us to study how κ of CeNiSn is affected by the Ni site substitution. As reference systems, we have measured κ of CePtSn, LaNiSn, and LaRhSb with the same crystal structure as in CeNiSn. CePtSn is a metallic dense Kondo compound which orders antiferromagnetically at a Neel temperature $T_N=7.5$ K and $T_M=5.0$ K.[23–25] The antiferromagnetic (AF) ordering is incommensurate with different modulation vectors both below T_M and T_N.

II. EXPERIMENT

The samples used in the present study are single crystals of CePtSn, CeNiSn #9, $CeNi_{0.95}M_{0.05}Sn$ (M=Co,Cu), and CeRhSb, and polycrystals of LaNiSn and LaRhSb. The single crystals of CePtSn, CeNiSn, and substituted ones were prepared by a Czochralski pulling method using a radio-frequency furnace. The quality of sample #9 is almost the same as that of sample #4 in Ref. 16. The single crystal of CeRhSb was prepared by the Bridgman method using a tungsten crucible. The polycrystals of LaNiSn and LaRhSb were prepared by arc melting. The thermal conductivity was measured by the usual steady-state method under the magnetic field up to 15 T and in the temperature range between 1.5 and 100 K. The temperature gradient was measured by Cernox thermometers. The temperature difference between both ends of the sample was 0.05–0.5 K, depending on the temperature region. We define the thermal conductivity along the a, b, and c axes as κ_a, κ_b, and κ_c, respectively, and the electrical resistivity along the a, b, and c axes as ρ_a, ρ_b, and ρ_c, respectively.

III. EXPERIMENTAL RESULTS

Figures 1 and 2 show the temperature dependencies for κ_a, κ_b, and κ_c of the CePtSn single crystal and the reduced Lorentz number L/L_0 obtained from κ and ρ, respectively. Here, $L=\kappa\rho/T$ and $L_0=24.5$ nW Ω K^{-2} is the Sommerfeld value. The increase in L/L_0 with decreasing temperature is often observed in dense Kondo compounds and is ascribed to the increase of the phonon contribution to κ with decreasing temperature, where the electronic contribution becomes smaller because of the large scattering of electrons by the Kondo effect.[26,27] The anisotropy of L/L_0 is observed, i.e., $(L/L_0)_a>(L/L_0)_c>(L/L_0)_b$. This anisotropy corresponds to that of the electrical resistivity, i.e., $\rho_a>\rho_c>\rho_b$. This means that the larger the electrical resistivity, the larger the phonon contribution to κ, which will be discussed later. Below ~10 K, L/L_0 decreases steeply, which may be related to the decrease of ρ accompanying the development of short-range AF ordering, as will be discussed below. While L/L_0 does not show any anomaly at T_N along any direction, that along the a axis shows a steeper decrease below T_M, as is seen in the inset in Fig. 2. This is clearly related to the

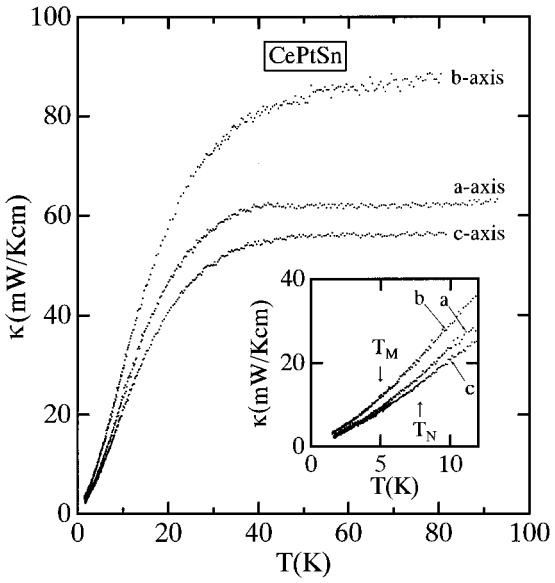

FIG. 1. Temperature dependence of the thermal conductivity along the a, b, and c axes of CePtSn single crystal. The inset shows those at low temperatures in an expanded scale. T_M and T_N indicate the AF ordering temperatures. See the text for details.

steeper decrease of ρ below T_M. These results suggest that the electron contribution to κ becomes larger below T_N compared to the phonon contribution, as a result of the decrease of the magnetic scattering of electrons by the antiferromagnetic ordering. The reason the decrease of L/L_0 is observed below ~10 K, which is slightly above T_N and an anomaly is not observed in L/L_0 at T_N may be due to the existence of the AF short-range ordering effect, which is seen in the results of the specific heat measurement.[24] Such a short-range-order effect on L/L_0 above the magnetic or quadrupole ordering temperature has been reported for CeB_6, PrB_6, and NdB_6.[27]

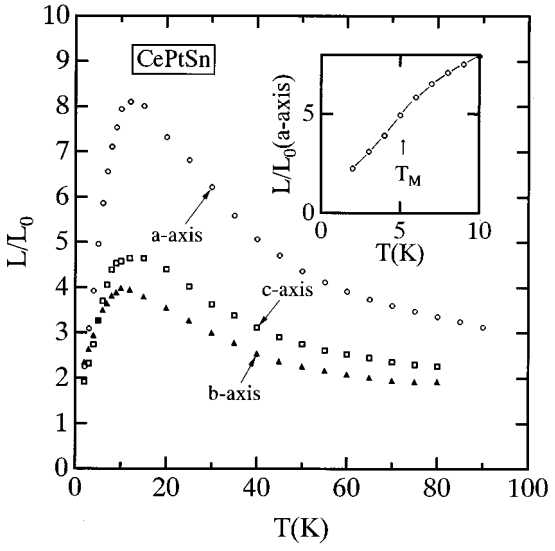

FIG. 2. Temperature dependence of the reduced Lorentz number L/L_0 along the a, b, and c axes of CePtSn. The inset shows that along the a axis at low temperatures in an expanded scale.

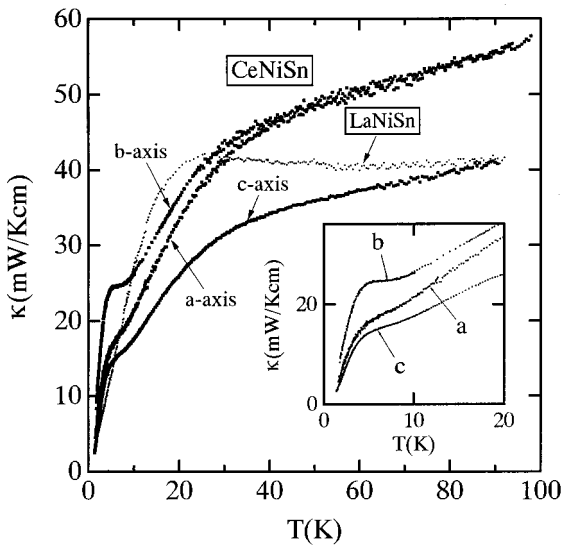

FIG. 3. Temperature dependence of the thermal conductivity along the a, b, and c axes of CeNiSn #9 single crystal and that of LaNiSn polycrystal. The inset shows those at low temperatures in an expanded scale.

Figures 3 and 4 show the temperature dependencies of κ_a, κ_b, and κ_c for CeNiSn #9 and LaNiSn and CeRhSb and LaRhSb, respectively. L/L_0 of LaNiSn obtained from κ and ρ is nearly 1 up to ~20 K, and after showing a shallow minimum around 30 K, increases and becomes ~1.3 at 100 K. This type of temperature dependence is usually observed in the normal metals. Below ~20 K, κ is dominated by impurity scattering and the heat current is carried mainly by electrons. The existence of the shallow minimum of κ is due to the inelastic scattering of electrons by phonons, and the phonon contribution becomes larger at higher temperatures.

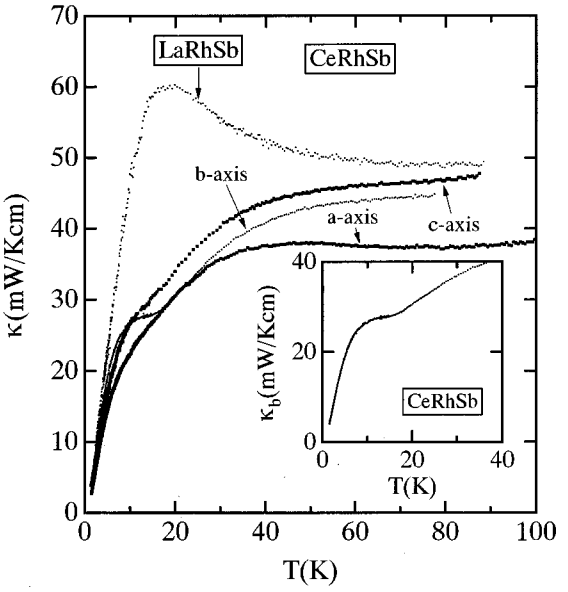

FIG. 4. Temperature dependence of the thermal conductivity along the a, b, and c axes of CeRhSb single crystal and that of LaRhSb polycrystal. The inset shows that along the b axis at low temperatures in an expanded scale.

LaRhSb also shows the normal behavior in $\kappa(T)$, whereas κ of CeNiSn and CeRhSb shows very anomalous behaviors. In CeNiSn, with decreasing temperature from 100 K, κ decreases gradually and steeply decreases below ~30 K. After showing an enhancement around 5 K, κ decreases very steeply with decreasing temperature. At high temperatures above ~20 K, while κ shows a similar temperature dependence along all the crystal axes, the magnitude of κ is different: $\kappa_a \sim \kappa_b > \kappa_c$. Near 5 K, the enhancement is much more pronounced in κ_b than in κ_a and κ_c. The anisotropic behavior of κ is observed also in CeRhSb, but the relation $\kappa_c > \kappa_b > \kappa_a$ at high temperatures is different from that in CeNiSn. The pronounced enhancement of κ_b similar to that in CeNiSn at ~5 K is observed around 10 K. These temperatures coincide with the temperatures of the maximum of specific heat divided by temperature, C/T in these two compounds, which was ascribed to the opening of the pseudogap.[4,6] This close coincidence between κ and C/T suggests that the enhancement of κ_b originates from the opening of the pseudogap. We note that the anisotropy of κ at low temperatures is a little different between CeNiSn and CeRhSb. In CeNiSn, the clear enhancement is observed in κ_a and κ_c, while they are rather smaller than that in κ_b. But in CeRhSb, no clear enhancement is observed in κ_a and κ_c.

Figures 5(a) and 5(b) show the temperature dependence of L/L_0 of CeNiSn #9 and CeRhSb, respectively. At high temperatures, L/L_0 increases with decreasing temperature, which indicates the increase of the phonon contribution with the decrease of temperature. When we compare the L/L_0 of the three compounds CePtSn, CeNiSn, and CeRhSb at high temperatures, it is found that L/L_0 (CeNiSn)$>$ L/L_0(CeRhSb)$>L/L_0$(CePtSn). The temperature dependencies of L/L_0 in CeNiSn and CeRhSb above ~10 K are similar to that of L/L_0 in CePtSn. The increase of L/L_0 below ~10 K in CeNiSn is much smaller than that in the impure sample.[21] This indicates that the large increase of L/L_0 in the impure sample is not intrinsic, but should be due to the extrinsic increase of ρ. It is necessary to investigate if the large increase of L/L_0 below ~10 K in CeRhSb depends on the sample quality or not. The steep decrease of L/L_0 along the a axis below ~3 K in CeNiSn is simply because ρ is nearly constant, but κ shows a steep decrease in this temperature region. Since the present result of $\kappa(T)$ agrees with the result of Isikawa *et al.* for an impure crystal,[21] we may assume that κ does not depend on the sample quality so much. The inset in Fig. 5(a) shows the temperature dependence of L/L_0 of CeNiSn using the present data of κ and resistivity data of CeNiSn #5 in Ref. 16, which is the best sample obtained at present. While L/L_0 along the a axis decreases below ~10 K, those along the b and c axes are still large at the lowest temperature measured here.

Figure 6 shows the temperature dependence of κ_b of $CeNi_{1-x}M_xSn$ (M=Co,Cu; x=0.05). The enhancement of κ_b around 5 K observed in CeNiSn is almost suppressed by 5% substitution. The results of NMR showed that the residual density of states at the Fermi level becomes larger with increasing the substitution and the pseudogap is almost destroyed by substituting 6% of Co or Cu for Ni.[14] Therefore, the observed enhancement of κ_b around 5 K in CeNiSn should be ascribed to the formation of the pseudogap. For

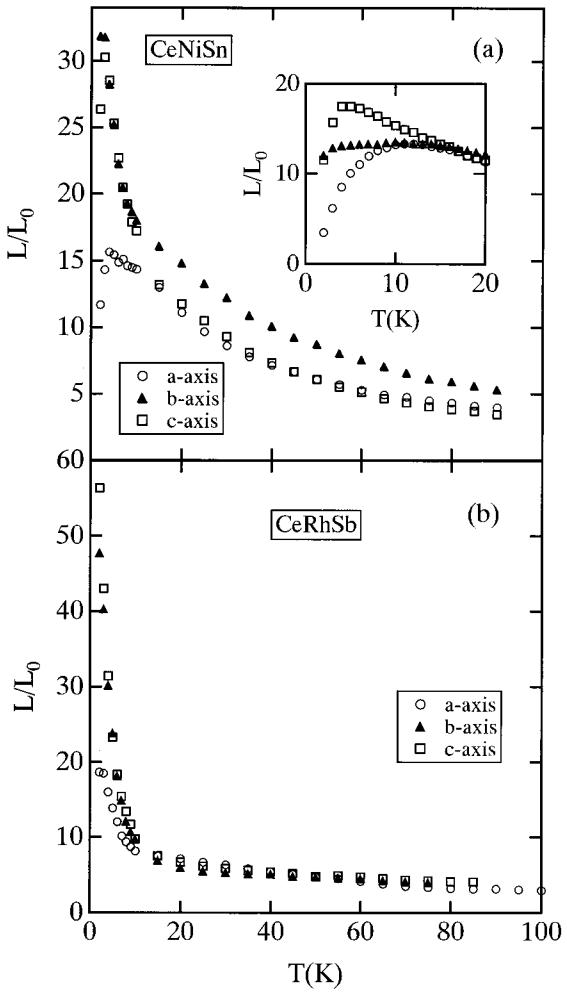

FIG. 5. Temperature dependence of the reduced Lorentz number L/L_0 along the a, b, and c axes of (a) CeNiSn #9 and (b) CeRhSb. The inset in (a) shows T dependence of L/L_0 along the a, b, and c axes of CeNiSn obtained from the present results of κ and resistivity data of CeNiSn #5 in Ref. 15.

these substituted samples, ρ increases with decreasing temperature, which is similar to results observed for an impure sample of CeNiSn.[16] However, there exists a significant difference in $\kappa(T)$ between the impure sample and the Ni site substituted ones. The enhancement of κ_b is easily suppressed by the Ni site substitution, whereas it remains in the impure sample containing segregated impurity phases.[21] This indicates that there is no correlation between the temperature dependence of ρ and κ in those samples. The present results are consistent with the NMR results showing that the existence of the pseudogap does not depend so much on the presence of impurity phases, but is easily suppressed by the Co and Cu substitution for Ni or La substitution for Ce.[14] Thus, it is clear that the enhancement of κ_b originates from the existence of the pseudogap. Then, it is expected that the anisotropic behavior of κ and ρ in the high-quality sample reflects the anisotropy of the pseudogap.

The pseudogap in CeNiSn is known to be destroyed by application of a magnetic field B along the a axis as mentioned above. Therefore, we studied the effect of the magnetic-field $B\|a$ axis on κ_b and represent the results in Fig. 7. Figure 8 shows the temperature dependence of κ_b of

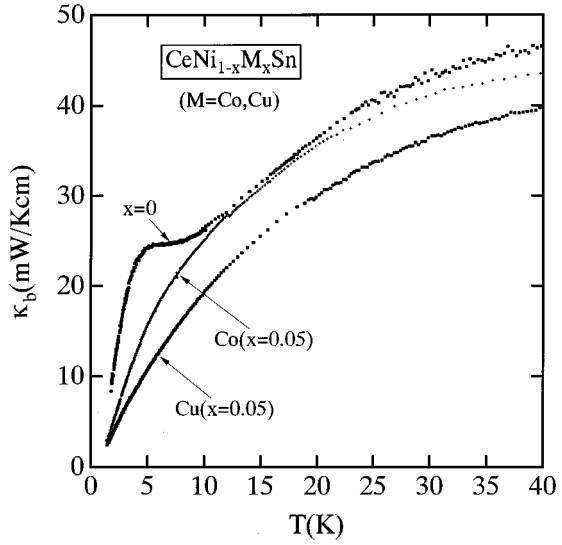

FIG. 6. Temperature dependence of the thermal conductivity of $CeNi_{1-x}M_xSn$ (M=Co,Cu) along the b axis.

CeNiSn #9 in various fields $B\|a$ axis. As for the magnetic-field dependence, there exist the following characteristics: With increasing magnetic field, the reduction of κ_b is pronounced below ~5 K, but becomes rapidly weaker at higher temperatures above ~8 K. The rapid suppression of κ_b around 5 K should originate from the destruction of the pseudogap by the magnetic field. In the temperature region between 1.8 and 4.3 K, κ_b at $B=15$ T becomes half that at $B=0$. At 4.3 K, κ_b steeply decreases around 6 T and bends around 8 T, while at 1.8 K, only a monotonous decrease is observed in κ_b. As for the magnetoresistance, the following results have been reported:[12] $\Delta\rho_b/\rho_b$ for the $B\|a$ axis is negative, and its magnetic-field dependence is similar to that

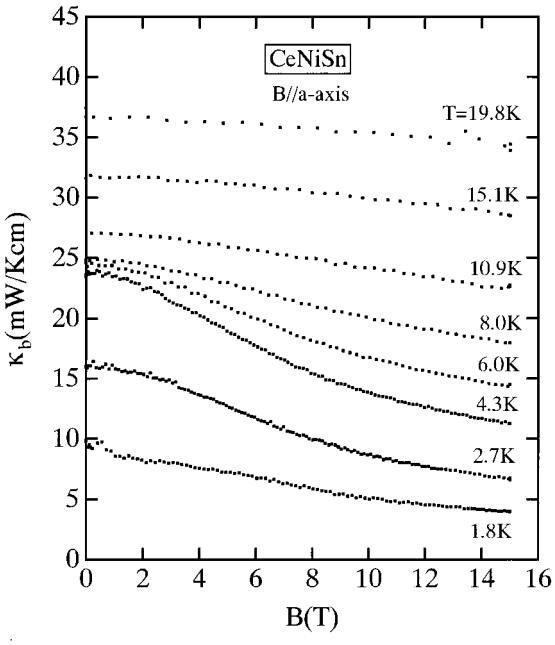

FIG. 7. Magnetic-field dependence of the thermal conductivity along the b axis of CeNiSn. The magnetic field $B\|a$ axis.

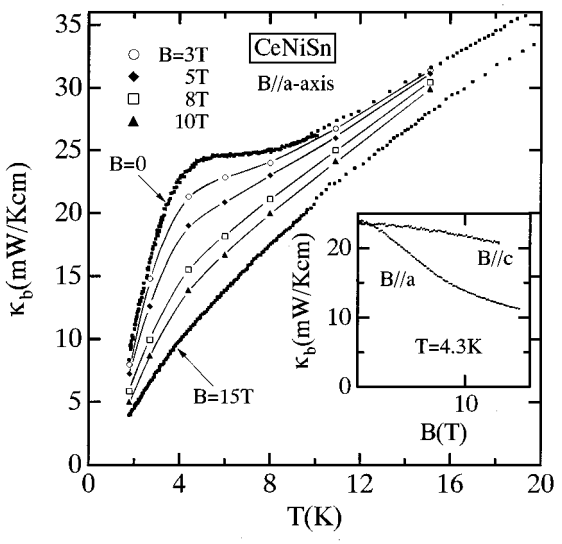

FIG. 8. Temperature dependence of the thermal conductivity along the b axis of CeNiSn under the magnetic field $B\|a$ axis. The inset shows the magnetic field dependence of κ_b of CeNiSn for $B\|a$ and c axes at 4.3 K.

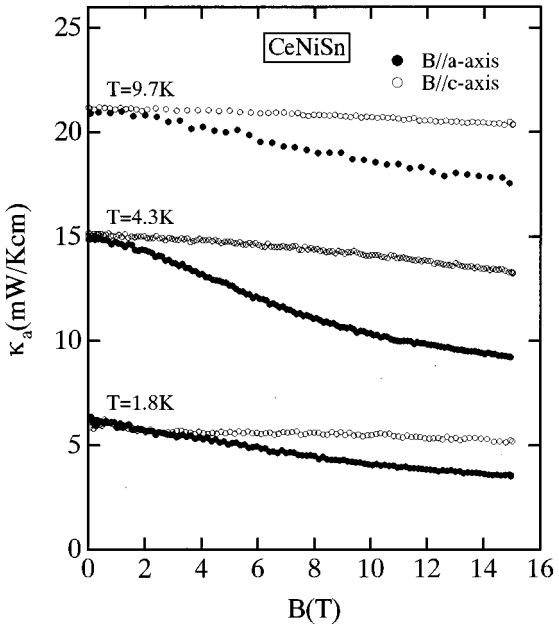

FIG. 9. Magnetic-field dependence of the thermal conductivity along the a axis of CeNiSn for $B\|a$ and c axes.

of κ_b. On the other hand, $\Delta\rho_b/\rho_b$ for the $B\|c$ axis is positive, while κ_b under the $B\|c$ axis shows a negative-field dependence as shown in the inset in Fig. 8. Thus, the magnetic-field dependence of κ_b is not correlated with that of ρ_b, although the field dependences of both κ_b and ρ_b would be associated with the suppression of the pseudogap by the magnetic field. The bendings of ρ_b and κ_b around 8 T for the $B\|a$ axis may reflect the field dependence of the destruction of the pseudogap. As for the temperature dependence of κ_b for $B\|a$, it is noteworthy that the enhancement of κ_b near 5 K is almost completely suppressed by the magnetic field of 15 T. The temperature dependence of κ_b for 15 T of the $B\|a$ axis is very similar to that of $CeNi_{0.95}Cu_{0.05}Sn$ in zero field. These results suggest that the pseudogap is almost destroyed by the magnetic field of 15 T. In the inset in Fig. 8, we compare the magnetic-field dependences of κ_b at 4.3 K for $B\|a$ and $B\|c$. It is seen that the reduction of κ_b for the $B\|c$ axis is much weaker than that for the $B\|a$ axis. A steep decrease is observed around 6 T for the $B\|a$ axis, whereas only a monotonous and weak decrease is observed for the $B\|c$ axis. This suggests that the anisotropic pseudogap is easily destroyed by the magnetic field $\|a$ axis corresponding to the easy axis of magnetization, but is not easily destroyed by that $\|c$ axis, which is consistent with previous results of other physical properties.[4]

Figure 9 shows the magnetic-field dependence of κ_a of CeNiSn #9 for $B\|a$ and $B\|c$. The reduction of κ_a for the $B\|a$ axis is $\sim$40% at $B=15$ T at 4.3 K. This value is comparable to that in κ_b for the $B\|a$ axis, while the enhancement of κ_a around 5 K in zero field is much smaller than that of κ_b, as is shown in Fig. 3. In the case of the $B\|c$ axis, while the negative-field dependence is observed in κ_a as in κ_b, the magnitude of the reduction of κ_a by the magnetic field is much smaller than that of κ_b. On the other hand, the magnetoresistance shows rather complex behavior.[16,28] $\Delta\rho_a/\rho_a$ for the $B\|a$ axis is positive up to $\sim$7 T and negative above $\sim$7 T. $\Delta\rho_a/\rho_a$ for the $B\|c$ axis is positive and its magnitude at low temperatures is very large, especially in the best sample #8, for which the cyclotron motion of electrons is proposed.[28] Even at 1.8 K, ρ_a at 15 T of the $B\|c$ axis reaches a value ten times larger than that in $B=0$. On the other hand, we find only a weak effect on κ_a at 1.8 K. Thus, the magnetic-field dependence of κ_a is not correlated with that of ρ_a. Namely, the large negative-field effect on κ is observed only for the $B\|a$ axis and a negative, but rather small effect for the $B\|c$ axis. In $CeNi_{0.95}Cu_{0.05}Sn$, the enhancement of κ_b around 5 K is almost completely suppressed in the zero magnetic field, and accordingly, the magnetic-field dependence shown in Fig. 10 is much weaker than that in CeNiSn.

IV. DISCUSSION

First we discuss the thermal conductivity of CeNiSn at high temperatures above $\sim$20 K, where the pseudogap is not formed in the electronic density of states. We attempt to separate the electronic contribution and the phonon one from the observed thermal conductivity. The large phonon contribution to κ is deduced from the large magnitude of L/L_0 in this compound. This may be related to the difference of the magnitude of ρ in these compounds, i.e., ρ(CeNiSn) $>\rho$(CeRhSb)$>\rho$(CePtSn). While all the compounds in the present paper are the Kondo compounds, such a relation between L/L_0 and ρ is observed also in RB_6 (R=Ce,Pr,Nd,Gd) at high temperatures; $L/L_0(CeB_6)>L/L_0(GdB_6)>L/L_0(NdB_6)\sim L/L_0(PrB_6)$ and $\rho(CeB_6)>\rho(GdB_6)>\rho(NdB_6)\sim\rho[(PrB_6)]$.[27] In RB_6, R^{3+} ions are well ionized and no anomalous behavior is expected except in CeB_6, which is the typical dense Kondo compounds. The results in RB_6 indicate that there does not exist a clear difference in L/L_0 between the Kondo compound and the localized system. This suggests that L/L_0 in the Kondo compound does not show anomalous behavior, at least at high temperatures. The results indicate that the magnitude of L/L_0 mainly depends on that of ρ and the larger L/L_0, the

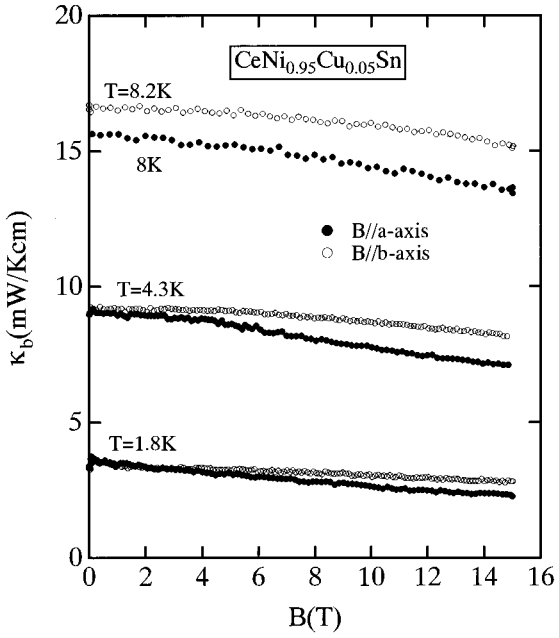

FIG. 10. Magnetic-field dependence of the thermal conductivity along the b axis of $CeNi_{0.95}Cu_{0.05}Sn$ for $B\|a$ and b axes.

larger the phonon contribution to κ. This means that when ρ is large, it is difficult for electrons to carry heat current due to the short relaxation time, and the phonon contribution becomes relatively larger. The present results show that this relation between L/L_0 and ρ holds true for the Kondo compounds, at least at high temperatures, and the phonon contribution to κ is largest in CeNiSn and smallest in CePtSn. If we apply the Wiedemann-Frantz law, the electronic part of the thermal conductivity κ_e^a, κ_e^b, and κ_e^c is estimated to be about ~15, ~12, and ~13 mW/K cm, respectively, at 100 K using the results of the electrical resistivity in Ref. 16. Next, we estimate the phonon contribution to the thermal conductivity as follows: The phonon thermal conductivity is written as $\kappa_{\rm ph}=C_{\rm ph}\nu_s^2\tau_{\rm ph}/3$ in the simplest form, where $C_{\rm ph}$, ν_s, and $\tau_{\rm ph}$ are the specific heat of the phonon, the sound velocity, and the relaxation time of the phonon, respectively. Since the velocity of the longitudinal sound wave is larger than that of the transverse sound wave, the former mainly contributes to $\kappa_{\rm ph}$. If $\tau_{\rm ph}$ is isotropic at high temperatures, $\kappa_{\rm ph}$ can be estimated by comparing the thermal conductivity with ν_s along three axis. The elastic constant C_{11}, C_{22}, and C_{33} along the a, b, and c axes at 100 K, respectively, are ~12.9, 12.5, and 8.2×10^{11} erg/cm^3, where C_{33} is ~50% smaller than the others.[29] Then, if $\tau_{\rm ph}$ is isotropic at high temperatures, $\kappa_{\rm ph}^a\sim\kappa_{\rm ph}^b\sim 1.5\kappa_{\rm ph}^c$, and it is estimated that $\kappa_{\rm ph}^a\sim\kappa_{\rm ph}^b\sim$38 mW/K cm, and $\kappa_{\rm ph}^c\sim$25 mW/K cm at 100 K. The observed values for κ_a, κ_b, and κ_c at 100 K are ~57, ~56, and ~43 mW/K cm, respectively, where κ_c is ~30% smaller than the others. The addition of the estimated values for the phonon contribution and the above estimated electronic contribution yields the total thermal conductivity which roughly agrees with the observed values. However, in the above estimation of $\kappa_{\rm ph}$, several assumptions are included. In order to verify the assumptions, the measurement of the sound velocity for CeRhSb is necessary where the anisotropy of ρ is small but that of κ is large, above ~50 K. The temperature dependences of L/L_0 above ~10 K in CeNiSn and CeRhSb are similar to that in CePtSn, suggesting that the electronic states at high temperatures in the Kondo semiconductors are not so different from those in the dense Kondo metals as mentioned above.

Next, we discuss the thermal conductivity at low temperatures. The temperature dependence of ρ sensitively depends on the sample quality, but that of κ does not depend on the sample quality. The latter is similar to the results of NMR (Ref. 14) and specific heat.[9] These indicate that the characteristic temperature dependences of κ are intrinsic, and κ is a good probe to see the pseudogap in these compounds. The present results indicate that the enhancement of κ_b around 5 and 10 K in CeNiSn and CeRhSb, respectively, originates from the opening of the anisotropic pseudogap in the density of states. We should address what contributes to the enhancement of κ_b at low temperatures. Some of the high-T_c cuprates exhibit a large enhancement in κ below T_c,[30] and YNi_2B_2C also shows such an enhancement of κ below $T_c=15.5$ K.[31] In these cases, the opening of a superconducting gap is the origin of the enhancement of κ. In the cuprates, the origin of the enhancement was ascribed to the enhancement of the relaxation time of quasiparticles.[32] In YNi_2B_2C, it was ascribed to the enhancement of the relaxation time of phonons, which is a consequence of the decrease of the number of conduction electrons as phonons scatter below T_c.[30] We consider whether the enhancement of κ_b in CeNiSn or CeRhSb is ascribable to that of the relaxation time of electrons, τ_e. If the Wiedemann-Franz law is applicable below $T_{\rm Gap}$, the large magnitude of L/L_0 at low temperatures indicates that the heat conductivity is dominated by phonons also at low temperatures. If τ_e increases with the opening of the pseudogap and is suppressed by destroying the pseudogap, both electrical conductivity and heat conductivity are expected to be enhanced in $B=0$ and suppressed by destroying the gap. However, the observed temperature and magnetic-field dependences of ρ and κ are not correlated with each other. If the Wiedemann-Franz law is applicable and the same quasiparticles carry both electrical and thermal currents below $T_{\rm Gap}$, it seems difficult to ascribe the enhancement of κ_b to the electronic origin. However, it should be noted that at present, we do not know the validity of the Wiedemann-Franz law below $T_{\rm Gap}$.

Next, we discuss the possibility that phonons mainly contribute to the enhancement of κ. In this case, as ν_s does not depend on the temperature at low temperatures,[29] the enhancement of κ should be ascribed to the enhancement of $\tau_{\rm ph}$. Then the present results suggest that when the gap is opened, $\tau_{\rm ph}$ is enhanced, and when it is closed, $\tau_{\rm ph}$ is reduced. The fact that the enhancement of κ is most pronounced along the b axis suggests such a possibility that the magnitude of the gap may be largest along this direction. Electrons are considered as the scattering center of phonons. When the gap is opened, $\tau_{\rm ph}$ increases as a result of the decrease of $N(\varepsilon_F)$ as was proposed by Isikawa *et al.*,[21] and when the gap is destroyed, $\tau_{\rm ph}$ decreases as a result of the increase of $N(\varepsilon_F)$. At present, we consider that the phonon scenario is more plausible because the magnetic-field dependences of κ and ρ are not correlated with each other. However, even in the case of the phonon scenario, there should exist the quasiparticle contribution to κ, and we really do not

know the nature of the quasiparticles below T_{Gap}. Further studies are necessary to clarify it.

Finally, we discuss the anisotropy of κ of CeNiSn and CeRhSb. As discussed above, κ is a good probe to investigate the nature of the gap in these compounds. In the present studies, we found the clear anisotropy in κ at low temperatures. As the enhancement of κ is considered to originate from the increase of τ_{ph} as discussed above, the anisotropy of this enhancement reflects the anisotropy of the gap. Ikeda and Miyake[11] predicted that the anisotropic gap vanishes along the *a* axis. An isotropic behavior in the *b*-*c* plane was expected because the anisotropy of the conduction band was not taken into account. In CeNiSn, the enhancement of κ around 5 K is largest along the *b* axis and smallest along the *a* axis and that along the *c* axis is smaller than that along the *b* axis, but is pronounced, which suggests a possibility that the gap is largest along the *b* axis and smallest along the *a* axis. This does not contradict the conjecture by Ikeda and Miyake, because the real band structure of CeNiSn may not be the simple isotropic one. On the other hand, in CeRhSb, the enhancement of κ along the *b* axis is largest, as in CeNiSn, but those along the *a* and *c* axes are very small and almost isotropic. This suggests that the gap in CeRhSb vanishes in the *a*-*c* plane. Thus, the nature of the anisotropic gap of CeRhSb seems to be different from that of CeNiSn. Further studies are necessary to clarify these different behaviors in κ and other physical properties between CeNiSn and CeRhSb.

V. CONCLUSION

In conclusion, we have studied the thermal conductivity κ of CeNiSn, Ce $\mathrm{Ni}_{0.95}M_{0.05}\mathrm{Sn}$ (M=Co,Cu), and CeRhSb single crystals and reference compounds, CePtSn single crystal, and LaNiSn and LaRhSb polycrystals. κ of LaNiSn and LaRhSb shows the behavior of normal metals and that of CePtSn shows the behavior observed in the dense Kondo metals, where the phonon contribution is larger than the electronic one because the electron relaxation time is short due to the Kondo scattering. The temperature dependence of the reduced Lorentz number L/L_0 of CeNiSn and CeRhSb at high temperatures is similar to that of CePtSn, which suggests that the electronic state of CeNiSn and CeRhSb at high temperatures is not so different from those of the dense Kondo metals. At low temperatures, however, the pronounced enhancement in κ is observed along the *b* axis in CeNiSn and CeRhSb around 5 and 10 K, respectively. On the other hand, in the same temperature region, κ along the *a* and *c* axes shows a weak enhancement in CeNiSn, but does not show a clear enhancement in CeRhSb. It is found that the enhancement of κ is almost completely suppressed by the magnetic field of 15 T along the easy *a* axis, and also by a small amount of substitution for Ni. This indicates that the origin of the enhancement of κ is the opening of the pseudogap and the suppression of κ by external forces originates from the recovery of $N(\varepsilon_f)$. The anisotropy of κ reflects that of the pseudogap which is largest along the *b* axis both in CeNiSn and CeRhSb.

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