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

M. Sera and N. Kobayashi
Institute for Materials Research, Tohoku University, 980-77 Sendai, Japan

T. Yoshino, K. Kobayashi, and T. Takabatake
Department of Materials Science, Faculty of Science, Hiroshima University, Higashi-Hiroshima 739, Japan

G. Nakamoto and H. Fujii
Faculty of Integrated Arts and Sciences, Hiroshima University, Higashi-Hiroshima 739, Japan

(Received 23 August 1996)

We have measured the thermal conductivity $\kappa$ for CeNiSn, CeNi$_{0.95}$M$_{0.05}$Sn ($M=\text{Co,Cu}$), and CeRhSb single crystals. The pronounced enhancement of $\kappa$ 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 $\kappa$ along the $b$ axis originates from the opening of the pseudogap in these compounds. On the other hand, the enhancement of $\kappa$ 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 $\kappa$ 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$_6$, YbB$_{12}$, and TmSe$_3$ etc., at low temperatures. In Ce compounds, while most of those have a metallic ground state, few compounds, CeNiSn, CeRhSb, and Ce$_3$Bi$_4$Pt$_3$ (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, specific heat, tunneling spectroscopy, etc., showed that the density of states at the Fermi energy, $N(E_F)$, decreases strongly below $\sim 10$ K, which was ascribed to the opening of the pseudogap. The nuclear spin-lattice relaxation rate $T_1^{-1}$ proportional to $T^3$ below $\sim 10$ K suggests that a pseudogap with a V-shaped structure opens at low temperatures. We define the temperature below which the pseudogap is opened as $T_{\text{Gap}}$. The mechanism of the anisotropic pseudogap formation was proposed by Ikeda and Miyake. The gap can be easily destroyed by external forces such as the magnetic field along the easy $a$ axis of magnetization, pressure, or a small amount of substitution. The negative magnetoresistance is largest for the $B\parallel a$ axis and smallest for the $B\parallel c$ axis. The same tendency has been observed in the specific heat and thermoelcetric power 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 $B\parallel a$ and most difficult to be destroyed for $B\parallel c$. The $a$ axis is the easy axis of magnetization $M$ and the $c$ axis is the difficult axis of $M$. 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 semiconducting behavior at low temperatures. However, now the sample quality becomes much better because of the progress of the sample preparation and purification. The isostructural CeRhSb also belongs to the category of the Kondo insulator and has also been extensively studied. The results of the specific heat and NMR, etc., suggest that the pseudogap opens below $\sim 20$ 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.

Isikawa et al. first reported the thermal conductivity $\kappa$ of the CeNiSn single crystal. Along the $b$ axis, $\kappa$ shows the minimum and the maximum at $\sim 6$ and $\sim 5$ K, respectively. It was argued that the maximum of $\kappa$ originates from the enhancement of the phonon relaxation time $\tau_{\text{ph}}$ because of the gap opening, in analogy with the mechanism proposed for the enhancement of $\kappa$ below $T_c$ in the high-$T_c$ cuprates by Uher and Kaiser. 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 $\tau_{\text{ph}}$ increases as a result of the strong decrease in the number of conduction electrons below the gap formation temperature. Hiess et al. measured $\kappa$ in a low-temperature region between $\sim 0.1$ and 6 K and concluded that $\kappa$ is dominated by phonons at low temperatures. 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, and therefore the temperature dependence of $\kappa$ 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 $\kappa$ 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 $\kappa$ along the $b$ axis originates from the opening of the gap,\textsuperscript{23,24} it should be affected largely by the magnetic field along the $a$ axis. The second purpose is to study how $\kappa$ 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.\textsuperscript{14} This prompted us to study how $\kappa$ of CeNiSn is affected by the Ni site substitution. As reference systems, we have measured $\kappa$ 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.\textsuperscript{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 $\kappa_a$, $\kappa_b$, and $\kappa_c$, respectively, and the electrical resistivity along the $a$, $b$, and $c$ axes as $\rho_a$, $\rho_b$, and $\rho_c$, respectively.

III. EXPERIMENTAL RESULTS

Figures 1 and 2 show the temperature dependencies for $\kappa_a$, $\kappa_b$, and $\kappa_c$ of the CePtSn single crystal and the reduced Lorentz number $L/L_0$ obtained from $\kappa$ and $\rho$, respectively. Here, $L=\kappa\rho/T$ and $L_0=24.5$ nW $\Omega$ 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 $\kappa$ with decreasing temperature, where the electronic contribution becomes smaller because of the large scattering of electrons by the Kondo effect.\textsuperscript{26,27} The anisotropy of $L/L_0$ is observed, i.e., $(L/L_0)_a>(L/L_0)_b>(L/L_0)_c$. 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 $\kappa$, which will be discussed later. Below $\sim 10$ K, $L/L_0$ decreases steeply, which may be related to the decrease of $\rho$ 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 steeper decrease of $\rho$ below $T_M$. These results suggest that the electron contribution to $\kappa$ 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 $\sim 10$ 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.\textsuperscript{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$_6$.\textsuperscript{27}
LaRhSb also shows the normal behavior in $\kappa(T)$, whereas $\kappa$ of CeNiSn and CeRhSb shows very anomalous behaviors. In CeNiSn, with decreasing temperature from 100 K, $\kappa$ decreases gradually and steeply decreases below $\sim 30$ K. After showing an enhancement around 5 K, $\kappa$ decreases very steeply with decreasing temperature. At high temperatures above $\sim 20$ K, while $\kappa$ shows a similar temperature dependence along all the crystal axes, the magnitude of $\kappa$ is different: $\kappa_a > \kappa_b > \kappa_c$. Near 5 K, the enhancement is much more pronounced in $\kappa_b$ than in $\kappa_a$ and $\kappa_c$. The anisotropic behavior of $\kappa$ is observed also in CeRhSb, but the relation $\kappa_a > \kappa_b > \kappa_c$ at high temperatures is different from that in CeNiSn. The pronounced enhancement of $\kappa_b$, similar to that in CeNiSn at $\sim 5$ 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.\textsuperscript{4,6} This close coincidence between $\kappa$ and $C/T$ suggests that the enhancement of $\kappa_b$ originates from the opening of the pseudogap.

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

LaRhSb also shows the normal behavior in $\kappa(T)$, whereas $\kappa$ of CeNiSn and CeRhSb shows very anomalous behaviors. In CeNiSn, with decreasing temperature from 100 K, $\kappa$ decreases gradually and steeply decreases below $\sim 30$ K. After showing an enhancement around 5 K, $\kappa$ decreases very steeply with decreasing temperature. At high temperatures above $\sim 20$ K, while $\kappa$ shows a similar temperature dependence along all the crystal axes, the magnitude of $\kappa$ is different: $\kappa_a > \kappa_b > \kappa_c$. Near 5 K, the enhancement is much more pronounced in $\kappa_b$ than in $\kappa_a$ and $\kappa_c$. The anisotropic behavior of $\kappa$ is observed also in CeRhSb, but the relation $\kappa_a > \kappa_b > \kappa_c$ at high temperatures is different from that in CeNiSn. The pronounced enhancement of $\kappa_b$, similar to that in CeNiSn at $\sim 5$ 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.\textsuperscript{4,6} This close coincidence between $\kappa$ and $C/T$ suggests that the enhancement of $\kappa_b$ originates from the opening of the pseudogap.\textsuperscript{4,6} This close coincidence between $\kappa$ and $C/T$ suggests that the enhancement of $\kappa_b$ originates from the opening of the pseudogap.\textsuperscript{4,6} This close coincidence between $\kappa$ and $C/T$ suggests that the enhancement of $\kappa_b$ originates from the opening of the pseudogap.\textsuperscript{4,6} This close coincidence between $\kappa$ and $C/T$ suggests that the enhancement of $\kappa_b$ originates from the opening of the pseudogap.

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 $\sim 10$ K are similar to that of $L/L_0$ in CePtSn. The increase of $L/L_0$ below $\sim 10$ K in CeNiSn is much smaller than that in the impure sample.\textsuperscript{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 $\rho$. It is necessary to investigate if the large increase of $L/L_0$ below $\sim 10$ K in CeRhSb depends on the sample quality or not. The steep decrease of $L/L_0$ along the $a$ axis below $\sim 3$ K in CeNiSn is simply because $\rho$ is nearly constant, but $\kappa$ 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,\textsuperscript{21} we may assume that $\kappa$ 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 $\kappa$ 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 $\sim 10$ K, those along the $b$ and $c$ axes are still large at the lowest temperature measured here.

Figure 6 shows the temperature dependence of $\kappa_b$ of CeNi$_{1-x}$M$_x$Sn ($M=\text{Co, Cu}; x=0.05$). The enhancement of $\kappa_b$ 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.\textsuperscript{14} Therefore, the observed enhancement of $\kappa_b$ around 5 K in CeNiSn should be ascribed to the formation of the pseudogap.
these substituted samples, \( \rho \) increases with decreasing temperature, which is similar to results observed for an impure sample of CeNiSn.\(^{16} \) However, there exists a significant difference in \( \kappa_b \) between the impure sample and the Ni site substituted ones. The enhancement of \( \kappa_b \) 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 \( \rho \) and \( \kappa_b \) 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 \( \kappa_b \) originates from the existence of the pseudogap. Then, it is expected that the anisotropic behavior of \( \kappa \) and \( \rho \) 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 \( B \parallel a \) axis. As for the magnetic-field dependence, there exist the following characteristics: With increasing magnetic field, the reduction of \( \kappa_b \) is pronounced below \( \sim 5 \) K, but becomes rapidly weaker at higher temperatures above \( \sim 8 \) K. The rapid suppression of \( \kappa_b \) 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, \( \kappa_b \) at \( B = 15 \) T becomes half that at \( B = 0 \). At 4.3 K, \( \kappa_b \) steeply decreases around 6 T and bends around 8 T, while at 1.8 K, only a monotonous decrease is observed in \( \kappa_b \). As for the magnetoresistance, the following results have been reported: \(^{12} \) \( \Delta \rho_b / \rho_b \) for the \( B \parallel a \) axis is negative, and its magnetic-field dependence is similar to that

FIG. 6. Temperature dependence of the thermal conductivity of CeNiSn \#9 in various fields \( B \parallel a \) axis. As for the magnetic-field dependence, there exist the following characteristics: With increasing magnetic field, the reduction of \( \kappa_b \) is pronounced below \( \sim 5 \) K, but becomes rapidly weaker at higher temperatures above \( \sim 8 \) K. The rapid suppression of \( \kappa_b \) 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, \( \kappa_b \) at \( B = 15 \) T becomes half that at \( B = 0 \). At 4.3 K, \( \kappa_b \) steeply decreases around 6 T and bends around 8 T, while at 1.8 K, only a monotonous decrease is observed in \( \kappa_b \). As for the magnetoresistance, the following results have been reported: \(^{12} \) \( \Delta \rho_b / \rho_b \) for the \( B \parallel a \) 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 \( B \parallel a \) axis.
of $\kappa_b$. On the other hand, $\Delta \rho_b/\rho_b$ for the $B||c$ axis is positive, while $\kappa_b$ under the $B||c$ axis shows a negative-field dependence as shown in the inset with Fig. 8. Thus, the magnetic-field dependence of $\kappa_b$ is not correlated with that of $\rho_b$, although the field dependences of both $\kappa_b$ and $\rho_b$ would be associated with the suppression of the pseudogap by the magnetic field. The bendings of $\kappa_b$ and $\rho_b$ 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 $\kappa_b$ for $B||a$, it is noteworthy that the enhancement of $\kappa_b$ near 5 K is almost completely suppressed by the magnetic field of 15 T. The temperature dependence of $\kappa_b$ 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 $\kappa_b$ at 4.3 K for $B||a$ and $B||c$. It is seen that the reduction of $\kappa_b$ 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.

Figure 9 shows the magnetic-field dependence of $\kappa_a$ of CeNiSn #9 for $B||a$ and $B||c$. The reduction of $\kappa_a$ for the $B||a$ axis is $\sim 40\%$ at $B=15$ T at 4.3 K. This value is comparable to that in $\kappa_b$ for the $B||a$ axis, while the enhancement of $\kappa_a$ around 5 K in zero field is much smaller than that of $\kappa_b$, as is shown in Fig. 3. In the case of the $B||c$ axis, while the negative-field dependence is observed in $\kappa_a$ as in $\kappa_b$, the magnitude of the reduction of $\kappa_a$ by the magnetic field is much smaller than that of $\kappa_b$. 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, $\rho_a$ 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 $\kappa_a$ at 1.8 K. Thus, the magnetic-field dependence of $\kappa_a$ is not correlated with that of $\rho_a$. Namely, the large negative-field effect on $\kappa$ 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 $\kappa_b$ 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 $\kappa$ is deduced from the large magnitude of $L/L_0$ in this compound. This may be related to the difference of the magnitude of $\rho$ in these compounds, i.e., $\rho$(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 $\rho$ is observed also in $RB_6$ ($R=$ Ce,Pr,Nd,Gd) at high temperatures; $L/L_0$(CeB$_6$) $>\rho$(CeB$_6$) $>\rho$(Ce$_2$B$_6$) $>\rho$(CeB$_6$) $>\rho$(GdB$_6$).$^{27}$ 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 $\rho$ and the larger $L/L_0$, the
larger the phonon contribution to \( \kappa \). This means that when \( \rho \) 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 \( \rho \) holds true for the Kondo compounds, at least at high temperatures, and the phonon contribution to \( \kappa \) is largest in CeNiSn and smallest in CePtSn. If we apply the Wiedemann-Franz law, the electronic part of the thermal conductivity \( \kappa_e^a \), \( \kappa_e^b \), and \( \kappa_e^c \) 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 \( \kappa_{\text{ph}} = C_{\text{ph}} v_\tau^3 \tau_{\text{ph}} / 3 \) in the simplest form, where \( C_{\text{ph}} \), \( v_\tau \), and \( \tau_{\text{ph}} \) 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 \( \kappa_{\text{ph}} \). If \( \tau_{\text{ph}} \) is isotropic at high temperatures, \( \kappa_{\text{ph}} \) can be estimated by comparing the thermal conductivity with \( v_\tau \) 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 \(~8.2\) \times \( 10^{11} \) erg/cm\(^3\), where \( C_{33} \) is \(~50\%) smaller than the others.\(^{29}\) Then, if \( \tau_{\text{ph}} \) is isotropic at high temperatures, \( \kappa_{\text{ph}} \approx 1.5\kappa_{\text{ph}}^b \approx 1.5\kappa_{\text{ph}}^c \approx 38\) mW/K cm, and \( \kappa_{\text{ph}}^a \approx 25\) mW/K cm at 100 K. The observed values for \( \kappa_a \), \( \kappa_b \), and \( \kappa_c \) at 100 K are \(~57\), \(~56\), and \(~43\) mW/K cm, respectively, where \( \kappa_c \) 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 \( \kappa_{\text{ph}} \), several assumptions are included. In order to verify the assumptions, the measurement of the sound velocity for CeRhSb is necessary where the anisotropy of \( \rho \) is small but that of \( \kappa \) 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 \( \rho \) sensitively depends on the sample quality, but that of \( \kappa \) 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 \( \kappa \) are intrinsic, and \( \kappa \) is a good probe to see the pseudogap in these compounds. The present results indicate that the enhancement of \( \kappa_b \) 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 \( \kappa_b \) at low temperatures. Some of the high-\( T_c \) cuprates exhibit a large enhancement in \( \kappa \) below \( T_c \),\(^{30}\) and YNi2B2C also shows such an enhancement of \( \kappa \) below \( T_c = 15.5\) K.\(^31\) In these cases, the opening of a superconducting gap is the origin of the enhancement of \( \kappa \). In the cuprates, the origin of the enhancement was ascribed to the enhancement of the relaxation time of quasiparticles.\(^{32}\) In YNi2B2C, 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 \( \kappa_b \) in CeNiSn or CeRhSb is ascribable to that of the relaxation time of electrons, \( \tau_e \). If the Wiedemann-Franz law is applicable below \( T_{\text{Gap}} \), the large magnitude of \( L/L_0 \) at low temperatures indicates that the heat conductivity is dominated by phonons also at low temperatures. If \( \tau_e \) 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 \( \rho \) and \( \kappa \) are not correlated with each other. If the Wiedemann-Franz law is applicable and the same quasiparticles carry both electrical and thermal currents below \( T_{\text{Gap}} \), it seems difficult to ascribe the enhancement of \( \kappa_b \) to the electronic origin. However, it should be noted that at present, we do not know the validity of the Wiedemann-Franz law below \( T_{\text{Gap}} \).

Next, we discuss the possibility that phonons mainly contribute to the enhancement of \( \kappa \). In this case, as \( v_\tau \) does not depend on the temperature at low temperatures,\(^{29}\) the enhancement of \( \kappa \) should be ascribed to the enhancement of \( \tau_{\text{ph}} \). Then the present results suggest that when the gap is opened, \( \tau_{\text{ph}} \) is enhanced, and when it is closed, \( \tau_{\text{ph}} \) is reduced. The fact that the enhancement of \( \kappa \) 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, \( \tau_{\text{ph}} \) increases as a result of the decrease of \( N(\varepsilon_F) \) as was proposed by Isikawa \textit{et al.},\(^{21}\) and when the gap is destroyed, \( \tau_{\text{ph}} \) 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 \( \kappa \) and \( \rho \) are not correlated with each other. However, even in the case of the phonon scenario, there should exist the quasiparticle contribution to \( \kappa \), and we really do not
know the nature of the quasiparticles below $T_{\text{Gap}}$. Further studies are necessary to clarify it.

Finally, we discuss the anisotropy of $\kappa$ of CeNiSn and CeRhSb. As discussed above, $\kappa$ is a good probe to investigate the nature of the gap in these compounds. In the present studies, we found the clear anisotropy in $\kappa$ at low temperatures. As the enhancement of $\kappa$ is considered to originate from the increase of $\tau_{\text{pu}}$, as discussed above, the anisotropy of this enhancement reflects the anisotropy of the gap. Ikeda and Miyake\textsuperscript{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 $\kappa$ 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 $\kappa$ 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 $\kappa$ and other physical properties between CeNiSn and CeRhSb.

V. CONCLUSION

In conclusion, we have studied the thermal conductivity $\kappa$ of CeNiSn, CeNi$_{0.95}$M$_{0.05}$Sn ($M =$ Co, Cu), and CeRhSb single crystals and reference compounds, CePtSn single crystal, and LaNiSn and LaRhSb polycrystals. $\kappa$ 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 $\kappa$ 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, $\kappa$ 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 $\kappa$ 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 $\kappa$ is the opening of the pseudogap and the suppression of $\kappa$ by external forces originates from the recovery of $N(e_f)$. The anisotropy of $\kappa$ reflects that of the pseudogap which is largest along the $b$ axis both in CeNiSn and CeRhSb.

ACKNOWLEDGMENTS

We are thankful to T. Otomo, H. Miura, S. Tanno, and K. Hohokura of the Tohoku University Cryogenic Center. This work was partly supported by Grant-in-Aid for Scientific Research (07454243) and Grant-in-Aid for Co-operation Research from the Ministry of Education, Science and Culture, Japan.