Electrical and Magnetic Properties of the Ni based Ternary Compounds $R_2NiGe_3$ ($R =$ Rare Earth Ions)

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Abstract. The crystal structure, electrical, and magnetic properties of the Ni based ternary compounds $R_2NiGe_3$ ($R =$ rare earth ions) have been investigated using powder X-ray diffraction, electrical resistivity, and magnetic susceptibility measurements. X-ray diffraction patterns reveal that all the samples studied crystallize in the AlB$_2$-derived hexagonal structure with space P6/mmm and the obtained values of the lattice constants $a$ and $c$ are $a = 0.4188(1)$ nm and $c = 0.4339(3)$ nm for La$_2NiGe_3$ and the lattice constants are found to decrease monotonically with increasing atomic number of R. A sudden drop to zero value in the $\rho(T)$ curve reveals that La$_2NiGe_3$ becomes superconducting with a midpoint transition temperature $T_C$ of ~ 0.45 K. The $\chi(T)$ curves for all samples studied follow the Curie-Weiss behavior for $T > 100$ K, with the obtained value of effective moment $\mu_{\text{eff}}$ close to the moment of the corresponding $R^{3+}$ ions. The occurrence of peak in the $\chi(T)$ curve and a drop off in the $\rho(T)$ curve at the corresponding temperatures indicate that antiferromagnetic transition occurs below 10 K in Gd$_2NiGe_3$ and Dy$_2NiGe_3$. In addition, Pr$_2NiGe_3$ and Ho$_2NiGe_3$ also become magnetically ordered at low temperatures as inferred from the drop off in the $\rho(T)$ curve and the anomaly in the $\chi(T)$ curves in these compounds. The existence of minimum at 18 K followed by a $-\ln T$ dependence below 18 K in the $\rho(T)$ curve and a $T^{1/2}$ dependence in the $\chi(T)$ curve observed for Ce$_2NiGe_3$ reveal characteristic of a Kondo lattice in this compound.

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1. Introduction
The ternary rare-earth (R) and actinide compounds crystallizing in AlB₂-derived hexagonal structure have attracted a lot of interest in the recent years because of their interesting properties [1]. For example, the Y₂PdGe₃ is a superconductor with a superconducting transition temperature ($T_c$) of 3 K [1,2], the Nd₂PdGe₃ compound exhibits magnetic ordering of a ferromagnetic type below 6 K [2], and Gd₂PdGe₃ orders antiferromagnetically below 10 K [3]. Recent report revealed that the AlB₂-derived hexagonal type ternary compound Ce₂NiGe₃ is a Kondo lattice compound that exhibits spin-glass behaviour due to the frustration and random distribution of Ni and Ge atoms on the crystallographic sites low temperatures [4, 5]. Recently, compounds with AlB₂-derived hexagonal structure and the Ni-based compounds have attracted a lot of research interest due to the observation of superconductivity in these systems. In this report, we present our results of the crystal structure, electrical, and magnetic properties of the R₂NiGe₃ (R = rare earth ions) compounds.

2. Experimental details
The polycrystalline samples of R₂NiGe₃ (R = rare earth ions) were prepared by arc-melting the stoichiometric amount of high purity elements (R: 99.99 %, Ni: 99.99 %, Ge: 99.999 %) together in a water cooled copper hearth in a Zr-gettered argon atmosphere. The alloy buttons were flipped over and re-melted carefully several times. A two-stage procedure was utilized with negligible weight loss (< 0.5 %). To improve the sample homogeneity, the as melted samples were subsequently wrapped in Ta foils, sealed in the evacuated quartz tubes and annealed at 800 °C for one week. The crystallographic data for all samples were obtained with powder X-ray diffractometer utilizing Cu Kα radiation. Ac electrical resistivity of the bar-shaped samples has been measured between 4.2 K and 300 K in a He⁴ cryostat using a four probe technique. De magnetic susceptibility measurements were performed in a commercial superconducting quantum interference device (SQUID) from 2 K to 300 K in an applied magnetic of 5000 Oe. In addition, a He³ refrigerator was used for measuring the resistivity data of La₂NiGe₃ for 0.3 K < T < 4 K.

3. Results and discussion
Powder X-ray diffraction patterns reveal that all the samples studied are of the of the hexagonal AlB₂-derived type structure. This is shown in Fig. 1(a), where the X-ray diffraction pattern and the Miller indices of the diffraction peaks for La₂NiGe₃ are plotted. Except for a small extra peak at 2θ = 33.691° (indicated by the star symbol) due to the existence of a tiny amount of the 122 phase, the X-ray pattern can be indexed with the AlB₂-derived hexagonal structure and the obtained values of the lattice parameters are $a = 4.188(1)$ Å and $c = 4.339(3)$ Å for La₂NiGe₃. In Fig. 1(b), the lattice parameters $a$ and $c$, and the unit cell volume $V$ for the R₂NiGe₃ compounds are plotted with respect to the rare earths.
The values of \( a \), \( c \) and \( V \) are found to decrease monotonically with increasing atomic number \( R \). The lanthanum contraction (monotonic decrease of \( a \) and \( c \)) observed here indicates that the rare earth ions in the \( R_2NiGe_3 \) compounds are trivalent at room temperature.

The normalized electrical resistance \( R(T)/R(300 \text{ K}) \) versus \( T \) curves for the \( R_2NiGe_3 \) (\( R = \text{La, Pr, Nd, and Gd} \)) compounds are plotted in Fig. 2(a) for \( 0 \text{ K} \leq T \leq 300 \text{ K} \). The \( R(T)/R(300 \text{ K}) \) curves for these compounds exhibit typical characteristics of a common metal and decrease monotonically with decreasing temperature \( T \). In addition, a change of the slope in the \( R(T)/R(300 \text{ K}) \) curve is observed at \( \sim 12 \text{ K} \) and \( 5.5 \text{ K} \) for \( \text{Pr}_2\text{NiGe}_3 \) and \( \text{Gd}_2\text{NiGe}_3 \), respectively (Fig. 2(b)), indicating the occurrence of magnetic ordering in these compounds. The low temperature \( \rho(T) \) curve for \( \text{La}_2\text{NiGe}_3 \) is plotted in the inset of Fig. 2(a). A sudden drop of the \( \rho(T) \) to zero value at \( T = 0.55 \text{ K} \) indicates that \( \text{La}_2\text{NiGe}_3 \) becomes superconducting with a mid-point transition temperature of \( 0.4 \text{ K} \). The drop off in the \( R(T)/R(300 \text{ K}) \) curve reveals that \( \text{Ho}_2\text{NiGe}_3 \) become magnetically ordered at \( \sim 8 \text{ K} \) (the \( \chi(T) \) curve is not shown here).

![Figure 2(a)](image1.png) ![Figure 2(b)](image2.png)

**Figure 2(a).** \( R(T)/R(300 \text{ K}) \) versus \( T \) curves for \( R_2NiGe_3 \) (\( R = \text{La, Pr, Nd, and Gd} \)). The inset depicts the \( \rho(T) \) curve for \( \text{La}_2\text{NiGe}_3 \) for \( T < 5 \text{ K} \).

**Figure 2(b).** Low temperature \( R(T)/R(300 \text{ K}) \) versus \( T \) curves for \( \text{Ho}_2\text{NiGe}_3 \), \( \text{Pr}_2\text{NiGe}_3 \) and \( \text{Gd}_2\text{NiGe}_3 \).

The magnetic susceptibility \( \chi \) and inverse susceptibility \( \chi^{-1} \) as a function of temperature \( T \) curves for \( R_2NiGe_3 \) (\( R = \text{Pr, Nd, Gd and Dy} \)) measured in an applied field of \( 5 \text{ kOe} \) for \( 0 \text{ K} \leq T \leq 300 \text{ K} \) are

![Figure 3(a)](image3.png) ![Figure 3(b)](image4.png)

**Figure 3(a).** \( \chi \) vs \( T \) and \( 1/\chi \) vs \( T \) of \( \text{Pr}_2\text{NiGe}_3 \) and \( \text{Nd}_2\text{NiGe}_3 \) measured in an applied field of \( 5 \text{ kOe} \). The inset depicts the \( d\chi/dT \) of \( \text{Pr}_2\text{NiGe}_3 \).

**Figure 3(b).** \( \chi \) vs \( T \) and \( 1/\chi \) vs \( T \) of \( \text{Gd}_2\text{NiGe}_3 \) and \( \text{Dy}_2\text{NiGe}_3 \) measured in an applied field of \( 5 \text{ kOe} \).
plotted in Fig. 3. The susceptibility data reveal that Nd$_2$NiGe$_3$ are nonmagnetic down to 2 K. The $\chi$ vs $T$ curve (inset of Fig.3(a)) for Pr$_2$NiGe$_3$ reveals the occurrence of two magnetic transitions at 12 K and 6.9 K, respectively. For $T > 50$ K, $\chi$ follows a Curie-Weiss behavior $\chi = C/(T - \Theta_p)$, with $\Theta_p = -0.61$ K and $-0.58$ K for Pr$_2$NiGe$_3$ and Nd$_2$NiGe$_3$, respectively. The effective moment obtained from the Curie constant $C = N\mu_{\text{eff}}^2/3k_B$ yield the values of $\mu_{\text{eff}} = 3.59$ $\mu_B$ per Pr ion and $\mu_{\text{eff}} = 3.65$ $\mu_B$ per Nd ion. The obtained values are close to that of the Pr$^{3+}$ ($\mu_{\text{eff}} = 3.58$ $\mu_B$) and Nd$^{3+}$ ($\mu_{\text{eff}} = 3.62$ $\mu_B$) ions. The $\chi(T)$ curve for Gd$_2$NiGe$_3$ reveals the occurrence of an antiferromagnetic transition at 8 K, near the temperature at which a change of the slope in the $R(T)/R(300$ K) curve was observed for this compound. The magnetic susceptibility curve for Dy$_2$NiGe$_3$ exhibits a peak at $T = 4.2$ K, which indicates the occurrence of antiferromagnetic ordering in this compound. The $\chi(T)$ curves for both compounds can also be described with the Curie-Weiss law for $T > 100$ K and the obtained values of the effective moment are $\mu_{\text{eff}} = 8.00$ $\mu_B$ per Gd ion and $\mu_{\text{eff}} = 10.68$ $\mu_B$ per Dy ion, respectively.

The susceptibility data (Fig. 4) reveal that Ce$_2$NiGe$_3$ are nonmagnetic down to 2 K and the susceptibility saturates gradually at low temperatures. The $\chi(T)$ curve for Ce$_2$NiGe$_3$ can be fitted with the Curie-Weiss law for $T > 100$ K and the obtained values of the effective moment are $\mu_{\text{eff}} = 2.57$ $\mu_B$ per Ce ion, a value that is close to the theoretical value of Ce$^{3+}$ ion (2.54 $\mu_B$). The $\rho(T)$ curve for Ce$_2$NiGe$_3$ reveals characteristics of a Kondo system. As shown in the inset of fig. 4, where the low temperature $\rho(T)$ curve for Ce$_2$NiGe$_3$ is plotted. The $\rho(T)$ curve exhibit a minimum at 18 K and followed by a $-\ln T$ dependence from 18 K to 6 K and drop off rapidly below 6 K. Such behaviour is typical of a Kondo lattice in the presence of crystal field effects [6, 7].

**Figure 4.** $\chi$ vs $T$ and $1/\chi$ vs $T$ of Ce$_2$NiGe$_3$ measured in an applied field of 5 kOe. The inset depicts the $\rho(T)$ curve for Ce$_2$NiGe$_3$ for $T < 50$ K.

In summary, we have studied the crystal structure, electrical, and magnetic properties of the R$_2$NiGe$_3$ (R = rare earth ions) compounds. We found that all the samples studied are of the AlB$_2$-derived hexagonal structure and the lattice constants $a$ and $c$ decrease monotonically with increasing atomic number of R. La$_2$NiGe$_3$ becomes superconducting with $T_C = 0.4$ K, Ce$_2$NiGe$_3$ is a Kondo lattice as inferred from the $\rho(T)$ data. Both $\chi(T)$ and $\rho(T)$ data indicate that antiferromagnetic transition occurs in Gd$_2$NiGe$_3$ and Dy$_2$NiGe$_3$, with transition temperature $T_N$ of 8 K and 4.2 K, respectively. In addition, Ho$_2$NiGe$_3$ also become magnetically ordered at ~ 8 K and Pr$_2$NiGe$_3$ exhibits two magnetic transitions at ~ 12 K and 5.5 K, respectively.

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