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Electrical and thermal transport in single nickel nanowire

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The thermal conductivity and electrical resistivity of a suspended nickel nanowire have been measured for $T=15-300$ K. The temperature dependence of the thermal conductivity and the Lorenz number strongly differ from the bulk. The comparison of the transports in the Ni nanowire shows, that at temperatures $75 < T < 300$ K Wiedemann–Franz (WF) law holds, whereas at temperatures $T < 75$ K the WF law is violated, indicating that thermal current in this material is suppressed more than electrical current. The results are explained by combined effect of confined dimension, enhanced disorder, and grown contribution of N-processes. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2839572]

Much attention has been focused on magnetic nanowires in recent years[1–8] due to their great importance in fundamental low-dimensional physics as well as in fabrication of nanoscale magnetic devices. To date, most of transport studies on ferromagnetic nanowires concentrated on electrical resistivity and magnetoresistivity, whereas the knowledge on heat transport on this material is suffering from the lack of information. This paper presents the study of electrical and thermal transport of suspended single nickel (Ni) nanowire.

Characteristic property of nanocrystalline materials, including nanowires, is the enhanced numbers of interfaces and random atomic arrangements, representing enhanced disorder. In consequence, the effective number of conduction electrons are limited to those, which pass or tunnel through all the boundaries along the mean free path (mfp), resulting in additional resistivity.[9–11] The grain size and transverse dimensions in nanowires are comparable to the mfp leading to the enhanced contribution of normal (N-processes) electron-phonon and electron-electron scattering at low temperatures[12] because in this case each scattering act is followed by a collision with the surface. There is also a considerable s-d scattering in ferromagnets, particularly in Ni,[13,14] which, for its turn, increases the number of N-processes, leading to redistribution of energy between hot and cold electrons. Thus, in nanowires the behavior of charge current may differ from the behavior of heat current, even if the heat carriers are also charged particles, giving rise to the violation of Wiedemann–Franz law (WF). Recently, the behavior of the Lorenz number (L) in disordered systems became the topic of several theoretical treatments, which suggested the deviation from the WF law in nonmagnetic granular metals,[15,16] and the correction ΔL of Lorenz number have to be positive.

The fabrication process of the suspended single nickel nanowire (Ni-NW) ($100\ \text{nm} \times 180\ \text{nm} \times 35\ \mu\text{m}$) includes: (1) thermal evaporation of Ni film and patterning it into strip with four electric leads by means of e-beam lithography and (2) the formation of a groove under the Ni strip by etching of a Si/Si_3N_4 substrate to thermally isolate the nanowire from the substrate. The Ni-NW is shown in Fig. 1. The junction-free connection of electrodes (the leads) prevents the undesirable heating of contact areas on the nanowire during the measurements. The thermal and electrical conductivities of the nanowire was measured simultaneously by means of "3ω self heating" method.[17] The whole set of arrangement was placed in a He^3 refrigerator which provides a variable temperature in high vacuum environment.

The experimental data of resistivity ρ of the Ni-NW in the temperature region of 0.5–300 K are shown in Fig. 2. The metallic temperature dependence of resistivity is similar to the bulk but with a larger magnitude of resistivity. The relative ratio of resistivity $\rho(300\ \text{K})/\rho(4.2\ \text{K})=2$ is much smaller as compared to the value of 47 for the bulk. Since the wire dimensions are much larger than the mfp of Ni (~ 14 nm),[18] the increase in resistivity is conjectured to be the predominant effect of the grain-boundary scattering. The temperature coefficient of resistivity (TCR) is positive in the whole temperature range (inset a in Fig. 2), indicating that the Ni-NW is weakly disordered. At low temperatures T

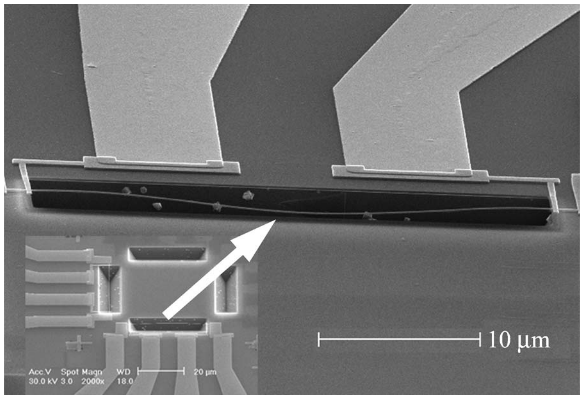

FIG. 1. The scanning electron microscope (SEM) image of the Ni-NW with dimensions $100\ \text{nm} \times 180\ \text{nm} \times 35\ \mu\text{m}$, the Ni-NW was suspended above a groove on a Si/Si_3N_4 substrate.

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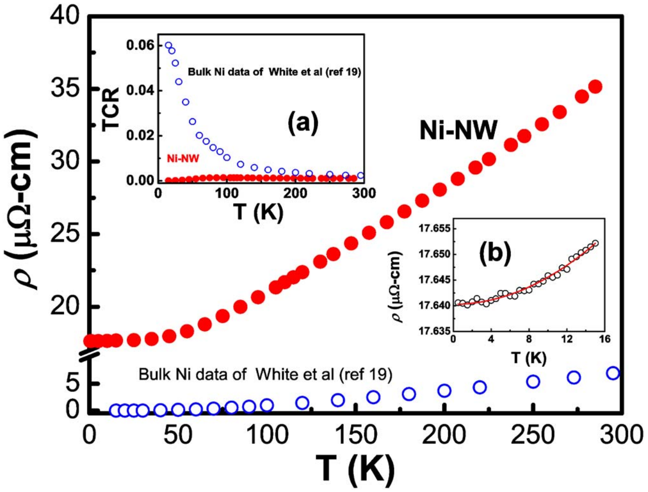

FIG. 2. (Color online) The resistivity $\rho(T)$ of the Ni-NW (solid circles) and the bulk (open circles) from White *et al.* Inset (a): the temperature dependence of TCR of the Ni-NW (solid circles) and the bulk (open circles) from White *et al.* Inset (b): the temperature dependence of resistivity of Ni-NW and the curve fit of $\rho=\rho_0+aT^n$, with $\rho_0=17.6\ \mu\Omega\,\mathrm{cm}$, $a=5\times10^{-5}\ \mu\Omega\,\mathrm{cm/K^2}$, and the power $n\sim2$.

<10 K, the temperature dependence of resistivity can be formulated as $\rho=\rho_0+aT^n$, with the power $n=2$ (inset b in Fig. 2). The consequence is similar to that of the bulk,[14] except the magnitude of residual resistivity $\rho_0=17.6\ \mu\Omega\,\mathrm{cm}$ is much larger than that of bulk Ni. The huge residual resistivity indicates an enhanced electronic scattering on interfacial boundaries and defects.

Although the nanowire still exhibits metallic behavior in $\rho(T)$ the situation in thermal conductivity is changed drastically. Figure 3 shows the experimental data of the thermal conductivity k in the temperature region of 15–300 K, representing a slight monotonic decrease of thermal conductivity with temperature decreasing. The much smaller $k(T)$ of the nanowire completely differs from that of the bulk (inset of Fig. 3).[19] The phenomena of the metallic electrical resistivity and decreasing thermal conductivity have been observed in disordered metallic systems of thin films, glasses, and concentrated alloys as well as in supperlattices.[20–23] Such behavior was explained by increased scattering of heat carrier with the structural defects and by the substantial contribution of the phonon thermal conductivity. In general, thermal conductivity k is the summation of electronic k_E and phonon k_{ph}. If the WF law holds, one can obtain the k_E from the data of $\rho(T)$ through the relation $k_E=L_0T/\rho$. The calculated k_E for $T<60$ K is larger than the experimental data k_{total}, indicating the violation of the WF law in this temperature region (Fig. 3). To estimate the phonon part of thermal conductivity k_{ph} for $T>100$ K, the k_E was subtracted from experimental k_{total}, the result of k_{ph} does not exceed 10% of total thermal conductivity k_{total}, and thus no considerable enhancement in the phonon part was observed at this temperature region (Fig. 3).

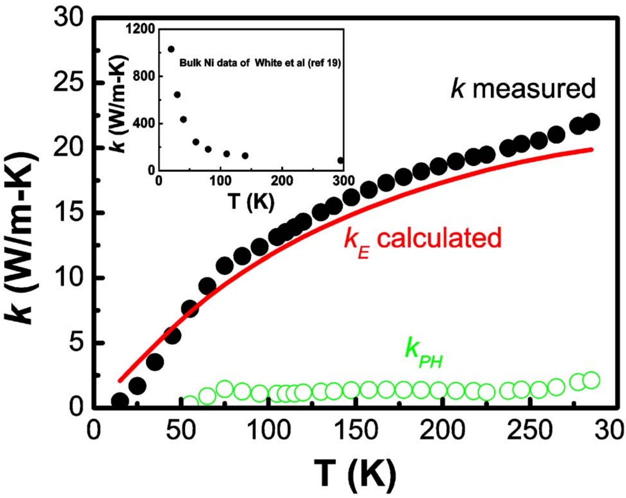

FIG. 3. (Color online) The thermal conductivity $k(T)$ of the Ni-NW (solid circles), the calculated k_E (solid line) and the k_{ph} (open circles). Inset: the thermal conductivity $k(T)$ of the pure bulk Ni Ref. 19.

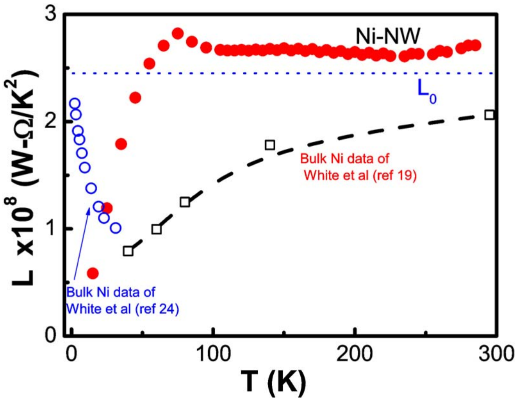

FIG. 4. (Color online) The Lorenz number $L(T)$ of the Ni-NW (solid circles) and the pure bulk Ni (open circles) Refs. 19 and 24.

To compare heat and charge currents the Lorenz number of the Ni-NW is calculated and plotted in Fig. 4. It is known[23] that in pure metals at temperatures higher than Debye temperature (θ_D) the Lorenz number approaches the Sommerfeld value $L_0=2.45\times10^{-8}\ \mathrm{W}\,\Omega/\mathrm{K}^2$, at $T<\theta_D$ it falls below L_0 and in the limit of low temperature region $T\to0$ K, L returns to L_0 again. Such kind of behavior of L was observed for bulk nickel (Fig. 4).[19,24] Unlike that of the bulk, Lorenz number of the Ni-NW is constant for $75<T<300$ K, although a little higher than the value of L_0, indicating both dominant electronic thermal conductivity k_E and large-angle scattering events mostly caused by elastic scattering at the grain boundaries. Based on the weak temperature dependence of electrical resistivity, the contribution to the thermal resistivity due to phonon scattering is relatively small. The small phonon thermal conductivity k_{ph} is likely the reason for the enhanced value of L in this temperature region. At $T<75$ K when mfp become comparable with grain size and transverse dimension of the Ni-NW, the contribution of small-angle scattering (N-process) grows. The small-angle scatterings relax only the heat current, leaving the charge current relatively unaffected,[25] which result in decreasing of the Lorenz number. Since the correction ΔL is the combined effects of positive contribution of the disorder ΔL_{dis} and negative contribution of the small-angle scattering (ee interaction) ΔL_{ee}, the variation in $L(T)$ is mainly depend on the relative weights of the two constituents.

In conclusion, we fabricated single suspended nickel nanowire and measured its electrical and thermal conductivities. The comparison of these two transports in the Ni-NW shows that at temperatures $75<T<300$ K WF law holds but not for $T<75$ K, indicating that thermal current in this material is suppressed more than electrical current. The results are explained by combined effect of confined dimension, enhanced disorder and grown contribution of N-processes.

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