Magnetism and the absence of superconductivity in the praseodymium–silicon system doped with carbon and boron

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\textbf{ARTICLE INFO}

Article history:
Received 6 February 2013
Received in revised form 4 March 2013
Available online 26 March 2013

Keywords:
Rare earth compound
Praseodymium silicide
Magnetism and superconductivity search for new phase
High-pressure high temperature

\textbf{ABSTRACT}

We searched for new structural, magnetic and superconductivity phases in the Pr–Si system using high-pressure high-temperature and arc melting syntheses. Both high and low Si concentration areas of the phase diagram were explored. Although a similar approach in the La–Si system produced new stable superconducting phases, in the Pr–Si system we did not find any new superconductors. At low Si concentrations, the arc-melted samples were doped with C or B. It was found that addition of C gave rise to multiple previously unknown ferromagnetic phases. Furthermore, X-ray refinement of the undoped samples confirmed the existence of the so far elusive Pr\textsubscript{3}Si\textsubscript{2} phase.

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1. Introduction

We investigated the Pr–Si system using high-pressure high-temperature (HP–HT) and arc melting syntheses with C and B doping. Following our previous search for superconductors in the La–Si system [1], we have extended the study to Pr–Si compounds. While much work has been done on the phase diagram of binary Pr-silicides, there are still a number of open questions [2]. For example, before this work, the existence of Pr\textsubscript{3}Si\textsubscript{2} was uncertain. The presence of Pr\textsubscript{3}Si\textsubscript{2} was first reported in Ref. [3], but has not been reproduced in more recent studies [2,4,5]. Magnetic and electrical properties of the binary system have also been extensively studied [5]. In the binary system there are six ferromagnetic compounds showing different Curie temperatures (\(T_C\)): Pr\textsubscript{3}Si\textsubscript{3} (\(T_C=42–44\) K) [5–7], Pr\textsubscript{5}Si\textsubscript{4} (\(T_C=40\) K) [5], PrSi (\(T_C=51–54\) K) [5,8], Pr\textsubscript{3}Si\textsubscript{4} (\(T_C=100–105\) K) [5,9], Pr\textsubscript{3}Si\textsubscript{5} (\(T_C=11.5\) K) [10] and Pr\textsubscript{3}Si\textsubscript{2} (\(T_C=11.5\) K) [11], as well as one antiferromagnetic compound, Pr\textsubscript{3}Si\textsubscript{2–\textsubscript{x}} (\(x=0.12\)), with the Neel temperature \(T_N=11\) K [5].

Our study includes two different regions of the phase diagram. To investigate the high Si concentration compounds, the Pr\textsubscript{3}Si\textsubscript{2} phase with an excess of Si was synthesized by HP–HT. High pressure synthesis is a unique technique which allows incorporation of elements into compounds which otherwise cannot be synthesized at ambient pressure. This technique, together with electron and hole doping, is commonly used to produce new superconductors [12,13]. It has been recently found that by HP–HT synthesis it is possible to stabilize two new superconducting compounds in the La–Si system: LaSi\textsubscript{5} and LaSi\textsubscript{10} with critical temperatures of 11.5 and 6.7 K respectively [14]. To explore the high Pr concentration binary compound Pr\textsubscript{3}Si\textsubscript{3}, we have synthesized by arc-melting Pr\textsubscript{3}Si\textsubscript{3} undoped and doped with C or B.

2. Experimental

2.1. Synthesis

For HP–HT synthesis of the Si highest concentration compounds, first Pr\textsubscript{3}Si\textsubscript{2} samples were prepared by arc-melting. Then, the Pr\textsubscript{3}Si\textsubscript{2} samples were grounded and mixed with Si (99.9995\%) powders to obtain the nominal composition Pr\textsubscript{3}Si\textsubscript{3}. Finally, the powders were synthesized by placing them in a Pt capsule in air atmosphere and compressed to 80 Kbar at 1100 °C for 30 min in a Belt type press.

To study the high Pr concentration phases, multiphase samples were prepared by arc-melting the constituents on a water-cooled copper hearth under purified argon atmosphere. High purity Pr...
The Curie temperature

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Pr5Si3B0.3, Pr5Si3B, Pr5Si3C0.3, Pr5Si3C1.5, Pr5Si3C2 and Pr5Si3C2. The samples were turned and remelted four times to ensure homogeneity. Total weight loss after arc-melting was less than 0.4%. After melting, the samples were wrapped in tantalum foil and sealed in evacuated quartz tubes for further annealing at 1000 °C for 5 days.

2.2. X-ray powder diffraction (XRD)

The synthesized metallic pellets were ground into a fine powder using an agate mortar and pestle to avoid preferred orientation which may produce misleading diffraction patterns. In-house XRD was initially Cu-Kα radiation. High resolution synchrotron powder diffraction (HRXRD) data were measured in a transmission capillary geometry using the mail-in program at beamline 11-BM of the Advanced Photon Source (APS), at Argonne National Laboratory, with a wavelength of 0.41352 Å. Discrete detectors covering an angular range from 2θ = −6° to 16° were scanned over a 34° 2θ range, with data points collected every 0.001° at a rate of 0.01 deg/s [15−17]. For the Rietveld refinement we used the EXPGUI software [18], a graphical interface for the GSAS package [19].

2.3. Magnetic characterization

Magnetic properties were characterized using a Quantum Design MPMMS SQUID magnetometer. For Zero Field Cooled-Field Cooled (ZFC-FC) magnetizations, the applied magnetic field was 100 Oe and the temperature was scanned in the 5−100 K range. In addition, dependence of magnetization on applied field was measured at different temperatures.

2.4. Magnetic field modulated microwave spectroscopy (MFMS)

MFMS is a unique technique that allows detection of micron-scale superconducting regions in inhomogenous systems faster and with higher sensitivity than most conventional methods [1,20]. MFMS is based on a measurement of temperature dependent phase sensitive microwave absorption while the sample is subjected to an AC modulated magnetic field. The AC field modulation together with phase sensitive detection is known to produce a sharp peak-like behavior across the superconducting transition [1,20]. The superconducting onset temperature is correlated with the temperature at which the MFMS signal falls below the background noise level. Non-superconducting transitions (pure magnetic transitions) have a different response at microwave frequencies. The absorption is dominated by the change of the surface resistance and skin depth as opposite on the SC transitions where the main absorption mechanism arises from the expulsion of the magnetic flux on the Meissner state [21].

3. Results and discussion

3.1. High pressure−high temperature synthesized PrSi2

XRD measurements show that the starting material (arc-melted PrSi2) is single phase tetragonal PrSi2 with space group I41/amd (Fig. 1). Magnetic properties of this phase (Fig. 2a) are consistent with previously reported data and show a FM transition at 11 K [11]. The FC curve of the magnetization data shows a drop. The Curie temperature $T_c$ is estimated from the midpoint of this drop. The peak observed in the ZFC curve is related to the Hopkinson effect (or Hopkinson peak) [22,23]: due to a decrease in the anisotropy before the magnetic order disappear the initial magnetization increases with increased temperature and exhibits a sharp maximum just below the Curie temperature.

After the HP-HT synthesis new XRD peaks appear (Fig. 1), and the maxima coming from the PrSi2 phase remains. All of the new XRD peaks could be attributed to intermetallic Pt-Si phases: Pt12Si5, PtSi and Pt6Si5. This indicates that the Pt capsule used in the HP-HT synthesis is reacting with the materials. In contrast to the La-Si system [14], no sign of the formation of a new PrSi2 phase has been found. After the HP-HT synthesis the PrSi2 XRD peaks are shifted, Fig. 1. The shift towards lower values is more pronounced in the planes along the z direction (notice, for example, the small shift in the (200) plane compared to the larger shift in the (004) plane). This shift indicates a change in the lattice parameter c, from 13.65 Å in the starting material to 13.84 Å in the HP-HT sample.

Magnetic characterization of the HP-HT sample (Fig. 2b), shows a strong paramagnetic component. The splitting of ZFC and FC magnetization curves at ~11 K indicates that the original FM component is still present. After the HP-HT synthesis the magnetization values at 5 K are reduced by an order of magnitude. This could be due to the change in the lattice parameters after HP-HT. MFMS scans were taken under FC conditions. For PrSi2 the signal shows absorption minima at 11 K, same as the FM transitions (Figs. 2a). For the HP-HT samples, MFMS response is flat in the temperature range (Fig. 2b), ruling out the presence of superconducting phases. No other features were observed in the temperature range studied. The minima-like behavior of these magnetic transitions can be explained in terms of the temperature dependence of the skin depth $\delta = 2\sigma_0/\omega_0$. The temperature dependence comes from the magnetic permeability $\mu(T)$ and the dc electrical conductivity $\sigma(T)$. Hence, an increase on the magnetic moment will show up as a minima-like behavior, as opposed to a superconducting transition which shows a sharp increase below the critical temperature [24].

3.2. Undoped Pr5Si3

HRXRD measurements of high Pr concentration samples were performed and a mixture of Pr5Si3 and Pr2Si2 phases was found.
As was mentioned in the introduction, the existence of a Pr$_3$Si$_2$ phase was previously uncertain. We performed Rietveld refinement to obtain quantitative results from x-ray synchrotron data and confirmed the existence of the Pr$_3$Si$_2$ phase. Fig. 3a shows the observed and calculated diffraction profile for one of the undoped samples. The result of the refinement gives a "chi squared" value of χ$^2_\chi=6.23$ and a "weighted profile R-factor" value of R$_{wp}=0.159$.

Table 1 shows the structures, lattice parameters and phase weight fractions of the Pr$_5$Si$_3$ and Pr$_3$Si$_2$ phases after the refinement. Fig. 3 (b) shows the HRXRD pattern focused around Q=2 Å$^{-1}$. In Fig. 3(a and b) the diffraction peaks coming from the Pr$_5$Si$_3$ and Pr$_3$Si$_2$ phases are indicated by tick marks. Only including the Pr$_3$Si$_2$ phase is possible to index all diffraction maxima and hence to obtain a good refinement. Thus, the presence of both phases (Pr$_5$Si$_3$ and Pr$_3$Si$_2$) and consequently the existence of Pr$_3$Si$_2$ are confirmed.

The magnetic characterization of the undoped sample (Fig. 4) shows that it is ferromagnetic at low temperatures and paramagnetic at high temperatures. The transition to a ferromagnetic order is at $T_C\sim 43$ K. This value agrees with that reported for Pr$_5$Si$_3$ single phase [5,6]. No other magnetic transitions have been observed, indicating that the Pr$_5$Si$_3$ phase does not show any ferromagnetic behavior. For Pr$_5$Si$_3$ single phase the saturation magnetization is 2.2μB/at [5]. For the samples studied here (Fig. 4a), at 10 K the saturation moment is 1.97 μB/at. This value corresponds to a Pr$_5$Si$_3$ weight fraction of 89% in the samples, which is in good agreement with the Rietveld refinement results (Table 1).

3.3. Doped samples: Pr$_5$Si$_3$B$_x$ and Pr$_5$Si$_3$C$_x$

Fig. 5 shows the HRXRD patterns for the undoped sample and three samples doped with C and B. The addition of C gives rise to the appearance of several diffraction peaks not present in the undoped sample. This is an indication of the presence of multiple phases. The presence of multiple XRD maxima in the samples...
makes identifying phases difficult. Therefore it is impossible to refine the structures. On the other hand, the addition of B produces new diffraction maxima that could be ascribed to the PrB4 phase (marked as dots in Fig. 5).

The addition of B in the system does not alter the magnetic properties. However, the addition of C in the system gives rise to the presence of multiple ferromagnetic transitions. Fig. 6 shows the ZFC–FC magnetization curves at 100 Oe for undoped sample. Insets: M vs. H at 10 K (a) and 80 K (b).

To identify the origin of the FM transitions we checked for the presence of other binary phases outside of the Pr–Si system: praseodymium oxides and praseodymium carbides as well as ternary compounds. Table 2 summarizes all the FM transitions found in the samples and shows the known binary (and ternary) Pr–Si–C phases which have FM transitions in those temperature ranges. According to the XRD patterns there are no indications that any of the binary oxides or carbides compounds are present in the samples. In addition none of these binary phases could explain the new magnetic transitions observed in the C doped samples. The oxides Pr2O3, Pr2O12, Pr2O16, Pr2O3, Pr11O20, Pr6O11 show no cooperative magnetism, [25] while PrO2 is antiferromagnetic with a Neel temperature of 14 K [26]. There are two antiferromagnetic carbides, Pr2C3 [27] with TN = 8 K and PrC2 [28] TN = 15 K. For PrC2 ferromagnetism has been also reported with TC = 7 K [29].

Pr3Si2C2 is the only ternary compound reported in literature. It is FM at low temperature, with a TC = 25 K [30]. Fig. 7 shows the simulated diffraction pattern corresponding to this ternary phase and the experimental data for the sample with intended composition Pr5Si3C3. In this sample the coexistence of Pr3Si2C2 along with other phases is clear. Thus, the observed FM transition at 20 K is likely due to Pr3Si2C2. This makes the magnetic transitions at 66 and 80 K the most interesting. These transitions might be related to the existence of new phases in the system because none of the Pr–silicides (or other ternary compounds) have transitions at these temperatures. Although Pr3Si4 has a FM transition at higher temperatures (~100 K), the presence of this Pr3Si4 phase is very unlikely according to XRD analysis.
### Table 2

Observed FM transitions divided in three temperature ranges. The corresponding Pr–Si binary (or ternary) phases having transition at the same temperatures are indicated.

<table>
<thead>
<tr>
<th>Compound (intended composition)</th>
<th>First magnetic transition ((T &lt; 40 , \text{K}))</th>
<th>Possible phase from literature</th>
<th>Second magnetic transition ((40 , \text{K} &lt; T &lt; 60 , \text{K}))</th>
<th>Possible phase from literature</th>
<th>Third magnetic transition ((T &gt; 60 , \text{K}))</th>
<th>Possible phase from literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pr₅Si₃</td>
<td>No</td>
<td>–</td>
<td>43 K</td>
<td>Pr₅Si₃</td>
<td>No</td>
<td>–</td>
</tr>
<tr>
<td>Pr₅Si₃B₂</td>
<td>No</td>
<td>–</td>
<td>43 K</td>
<td>Pr₅Si₃</td>
<td>No</td>
<td>–</td>
</tr>
<tr>
<td>Pr₅Si₃B</td>
<td>No</td>
<td>–</td>
<td>43 K</td>
<td>Pr₅Si₃</td>
<td>No</td>
<td>–</td>
</tr>
<tr>
<td>Pr₅Si₃C₂</td>
<td>20 K</td>
<td>Pr₅Si₃C₂</td>
<td>43 K</td>
<td>Pr₅Si₃</td>
<td>80 K</td>
<td>Unknown</td>
</tr>
<tr>
<td>Pr₅Si₃C</td>
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<td>Pr₅Si₃C</td>
<td>52 K</td>
<td>PrSi</td>
<td>80 K</td>
<td>Unknown</td>
</tr>
<tr>
<td>Pr₅Si₃C₁₅</td>
<td>No</td>
<td>–</td>
<td>52 K</td>
<td>PrSi</td>
<td>80 K</td>
<td>Unknown</td>
</tr>
<tr>
<td>Pr₅Si₃C₂</td>
<td>20 K</td>
<td>Pr₅Si₃C₂</td>
<td>43 K</td>
<td>Pr₅Si₃</td>
<td>66 K</td>
<td>Unknown</td>
</tr>
<tr>
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<td>Pr₅Si₃C₃</td>
<td>No</td>
<td>–</td>
<td>66 K</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

Fig. 7. X-ray diffraction patterns for sample Pr₅Si₃C₃ (thin red lines). Simulated X-ray diffraction pattern for phase Pr₅Si₃C₂ (thick blue lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Conclusions

We have investigated structural and magnetic properties in the Pr–Si system in two different regions of the phase diagram. The highest Pr concentration area was doped with C and B. In the Pr₅Si₃ compounds we used HP–HT synthesis. Fast screening using MFEMS measurements indicates the absence of superconductivity in our samples. The addition of C to the Pr₅Si₃ phase gives rise to several phases and new magnetic transitions. Unfortunately, the XRD patterns for C doped samples show multiple peaks and the identification of new phases was not possible. Doping the system with B creates a Pr₅B₂ phase and no new magnetic transitions have been observed. XRD studies and Rietveld refinement of undoped sample confirm the existence of the so far elusive Pr₅Si₃ phase.

Acknowledgments

We acknowledged the 11-BM beamline staff for their support in the HRXRD measurements. This work was supported by an AFOSR MURI grant, no. F49550-09-1-0577. Use of the Advanced Photon Source at the Argonne National Laboratory was supported by the U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

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