

ADVANCED THERMOELECTRIC MATERIALS  
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TRANSITION METAL SILICIDES  
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## I. INTRODUCTION

Thermoelectric energy conversion has proven a reliable source of power under the demanding conditions of space. Radioisotope and nuclear reactor heat sources have been combined with devices constructed from various thermoelectric materials including chromel-alumel, bismuth telluride, lead telluride and silicon germanium. Such devices have provided many years of uninterrupted power. A thermoelectric system consists of heat source, heat rejection and conversion components each of which presents challenges and can limit device performance. The heat source and rejection systems define the ultimate limits on system weights and power. The efficiency of the converter, which represents a relatively small investment in weight in itself, determines overall system performance because regardless of the total thermal flux made available by the heat source and rejection systems, it is the converter which actually produces the electrical power.

The converter in turn is largely defined by the choice of thermoelectric materials. Many device geometries with various advantages and disadvantages are possible and have been employed, but the thermoelectric material imposes an upper limit to device performance. State-of-the-art silicon germanium alloys, for example, impose an upper limit on conversion efficiency of about 8.6% on a device operating between 600 K and 1300 K (or about 5.6% on a device operating between 800 K and 1300 K). Actual efficiencies achieved are not much lower than this, indicating how effective current designs are at utilizing existing materials. Theoretical (Carnot) efficiency is 54% (38% for  $T_c=800$  K) for such a device. Solid state theory provides no intrinsic reason for the low efficiency of thermoelectric materials. The margin for growth over current materials of about a factor of 6 in conversion efficiency justifies the search for improved materials.

This program seeks to identify candidate thermoelectric materials with the potential for significantly better performance compared to current silicon-germanium alloys. The following properties, in approximate order of priority, are desired:

- 1) chemical, thermal and structural stability to at least 1300 K;
- 2) low lattice thermal conductivity;
- 3) high charge carrier mobility;
- 4) dopable to both n- and p-type;
- 5) dopable to the extrinsic regime at the highest operating temperatures;
- 6) capable of good electrical and thermal connections;
- 7) fabrication by conventional methods.

The ideal material would meet all of these requirements. A promising material may fail to meet some of these requirements, but compensate by being extremely attractive in some other respects. In some cases, certain applications may place different emphasis on various requirements. Applications with only limited life requirements may relax the stability requirement. Some applications might be sufficiently performance sensitive that non-conventional preparation methods may be considered since this is largely a cost consideration, both in terms of production of practical materials and in terms of the development time and costs.

The current program seeks materials consistent with space power applications such as the General Purpose Heat Source (GPHS) radioisotope generators and the SP-100 nuclear reactor programs. A successful materials program might well be expected to provide motivation for entirely new space power efforts based on the new materials. The SP-100 program, for example, might have been built of advanced thermoelectric materials (rather than the silicon-germanium based materials currently planned for this program) had sufficient materials development progress been achieved.

Transition metal silicides have been investigated in 1986 as potentially high figure of merit thermoelectric materials. Many silicon-rich silicides of column VII and VIII transition metals have been reported in the literature to be semiconductors. Silicides of the 3-d transition metals manganese, iron and cobalt have all been investigated to some extent. Although not without some attractive features, these materials are generally insufficiently refractory for use at 1300 K. Silicides of the 4-d and 5-d transition metal elements ruthenium, rhodium, rhenium, osmium and iridium have higher melting points and in some cases have been reported to be semiconductors, however relatively little data are available.  $\text{OsSi}_2$  in particular has been reported to have a band gap of 1.8 eV, much larger than the band gap of silicon of about 1.1 eV, and therefore should be relatively immune to the onset of intrinsic conduction at high temperatures which can limit the usefulness of an otherwise attractive material.

The crystal structure of  $\text{OsSi}_2$  is reported to be the same as  $\text{ss-FeSi}_2$ , known to be a fairly attractive thermoelectric. The heavier osmium compound is expected to have a lower thermal conductivity and similar electronic properties and therefore may be a better thermoelectric and also useful at higher temperatures, due to its higher melting point. Interestingly,  $\text{RuSi}_2$  has not been reported although it must exist if the osmium and iron compounds both exist. Similar arguments can be made for other transition metal silicides. The bonding in many of these crystal structures leads to a tetrahedral environment around the silicon atoms suggesting an electronic structure similar to that in silicon may occur. The heavier transition elements and more complex crystal structures suggest these materials might have lower thermal conductivities than silicon. These general properties coupled with the greater chemical flexibility to tailor material properties afforded by the binary compounds, compared with alloys of elements alone

such as Si-Ge alloys, is very promising for materials development activities.

## II EXPERIMENTAL DETAILS

Eleven samples were prepared by direct reaction from the elements. Stoichiometric amounts of -325 mesh powders were mixed until uniform, as indicated by visual inspection. Approximately five grams of powder were loaded into a split graphite mold, 0.5" in diameter. The graphite mold and pistons were treated with boron nitride to act as a mold release. The powders were heated in vacuum to a temperature about 100 K less than the anticipated melting temperature of the compound. 10 kpsi was applied for 30 minutes, the pressure released and the compact ejected from the die. Furnace power was then removed and the sample allowed to cool. X-ray diffraction measurement were performed on eight samples and compared to literature x-ray diffraction patterns.

This sample preparation procedure has the advantage of being quick and simple and has produced some excellent samples. As a semiconductor preparation technique, however, the approach is quite crude. Contamination from container walls, incomplete reaction and loss of charge material can result in alteration of stoichiometry perhaps with disastrous effects on transport properties, particularly the Seebeck coefficient and the electrical resistivity. As a survey technique this approach has proven satisfactory, however improvements are recommended for the following phase of effort.

Hall effect measurements were attempted on all samples prepared using a Van de Pauws technique developed for use on SiGe alloys. In most cases high, non-ohmic contact resistances interfered with accurate determinations. While this type of measurement complication is not uncommon and often fairly

readily solved, sample quality was not generally good enough to justify special efforts to obtain accurate mobility measurements.

Thermal diffusivity performed from 200 C to 1000 C on seven samples using a Theta Industries laser flash diffusivity apparatus. Thermal conductivity was calculated using the measured thermal diffusivity and density and heat capacity calculated using the Debye theory. The heat capacity two samples, one of which was SiGe, was measured using a Perkin Elmer differential scanning calorimeter (DSC) and found to agree with the calculated Debye heat capacity to within 10%. The heat capacity is a bulk, thermodynamic quantity and the Debye value is usually fairly reliable at high temperatures. The use of calculated values of heat capacity in the determination of the thermal conductivity probably does not introduce more than about a 20% error in the thermal conductivity, which is sufficient for surveys of this kind. Relative values of the thermal conductivities are probably more reliable than this. Differential thermal analysis was also performed on one sample.

The high temperature electrical resistivity was determined on two samples using a special fixture designed to handle small samples. The fixture suspends a 0.5" diameter samples between four thermocouples equally spaced around the perimeter of the sample. Using one neighboring pair of leads as current probes and the second pair as voltage probes, the electrical resistivity may be determined. The thermocouples are held in place by tungsten springs in a sapphire fixture. Originally intended to allow the determination of the Seebeck coefficient in addition to the electrical resistivity, test runs on SiGe indicated large errors in the Seebeck determination. Analysis of the data obtained in these test runs indicate the main source of error was a temperature drop across the joint of the thermocouples. Estimates indicate this error might have been reduced to

the 10%-15% range in some cases, but probably not better than this. The essential problem is that the heat flux which supplies the temperature gradient must, in this geometry, flow through the thermocouples. A better geometry would hold the sample in such a way that very little heat flows through the thermocouple itself, which requires some auxiliary support system. This feature will be incorporated in the next version of the Seebeck measuring experiment.

### III RESULTS

Table 1 summarizes the samples prepared in 1986. Some of the physical properties of these samples are summarized in Table 2. Since no attempt was made to dope samples, a wide range of Seebeck coefficient values were typically observed within a given sample, depending on the point at which the probe contacted the sample. The range of observed Seebeck values are given in Table 2. We will first discuss those samples which contain neither Ru nor Os. The phase diagrams of the Ir-Si and Rh-Si systems have not been reported, but a variety of crystal structure types have been reported. Three silicon rich Ir-Si compounds, Ir<sub>3</sub>Si<sub>5</sub>, IrSi<sub>2</sub> and IrSi<sub>3</sub>, and two silicon rich Rh-Si compounds, Rh<sub>2</sub>Si<sub>3</sub>, RhSi<sub>2</sub> have been reported. At least some of these can be expected to be fairly large band gap semiconductors.

Two samples prepared in this study, 59 with nominal composition Ir<sub>3</sub>Si<sub>5</sub> and 60 with nominal composition Rh<sub>3</sub>Si<sub>5</sub>, resulted in very complex x-ray diffraction patterns representing more than one phase. In both cases considerable loss pressure was observed during the hot pressing and large amounts of material extruded through the dies. This behavior suggests the presence of a relatively low melting point phase in each case. These systems will require an approximate determination of the phase diagrams, at least in the silicon-rich region, before significant progress can be made.



The Ir-Si sample exhibited p-type Seebeck values, some of which were as large as 287  $\mu\text{V}/\text{K}$ , indicative of the semiconducting nature of at least some of the sample. The Seebeck values for the Rh-Si sample were uniformly small and negative and the resistivity was quite small, indicating the metallic nature of this sample. While more extensive study is certainly recommended, no further work on the Ir-Si or Rh-Si systems was pursued in this study.

$\text{CrSi}_2$  and  $\text{ReSi}_2$  have been reported in the literature as semiconductors and one sample of  $\text{CrSi}_2$ , 50, and two samples of  $\text{ReSi}_2$ , 61 and 63, were prepared. Large Seebeck coefficient and carrier mobility values were observed (see Table 2), which indicates reasonable electrical properties may be possible in these materials. The thermal conductivity, calculated using the measured thermal diffusivity and density with a heat capacity value calculated from the Debye model (see Table 2), is shown for  $\text{CrSi}_2$  and  $\text{ReSi}_2$  in Figure 1. The thermal conductivity of these two samples is significantly higher than  $\text{SiGe}$ , also shown in Figure 1. Literature values reported for the same compounds suggest thermal conductivity values comparable to  $\text{SiGe}$  are possible, so these compounds are also probably worth further investigation.

While the Cr, Re, Ir and Rh silicides are all semiconductors with the potential for significantly improved figure of merit values, the Os-Si and Rh-Si systems appear more promising at this time. Three Ru-Si samples, 55  $\text{Ru}_2\text{Si}_3$ , 56  $\text{RuSi}_2$  and 64  $\text{RuSi}_{1.8}\text{Ge}_{0.2}$  and two Os-Si samples, 58  $\text{Os}_2\text{Si}$   $\text{OsSi}_2$ , were prepared in this study. X-ray diffraction indicated all of these samples were predominantly of the  $\text{Ru}_2\text{Si}_3$ -type crystal structure, which appears to be fairly stable. While  $\text{OsSi}_2$  exists, none of these samples were of predominantly this phase, although sample 58 may have traces of this compound in it as indicated by the x-ray diffraction pattern. The thermal conductivity values of these samples (see Figures 1 and 2) are lower than

SiGe at high temperatures.

The RuSi<sub>2</sub> sample exhibits a remarkably low thermal conductivity, as low as 0.012 W/cm-K, more than a factor of 3 below that of SiGe. The reason for the especially low thermal conductivity in this particular sample is not clear at this time and should be studied more closely. Since doping and alloying are expected to lower the thermal conductivity even further, these materials appear quite attractive from the point of view of thermal conductivity, compared to SiGe. Figure 3 shows the electrical resistivity of Ru<sub>2</sub>Si<sub>3</sub> and Os<sub>2</sub>Si<sub>3</sub> as prepared and measured in this study. For comparison, a sample of undoped SiGe is also shown in this figure. The high temperature slope indicates the band gap of the sample and these are also shown in Figure 3. While Ru<sub>2</sub>Si<sub>3</sub> and Os<sub>2</sub>Si<sub>3</sub> have somewhat smaller band gaps (0.71 eV and 0.88 eV, respectively) than SiGe (1.19 eV), they are still large enough to be useful at high temperatures. Although room temperature mobility values were not determined due to inadequacy of the existing apparatus, the similarity of the resistivity data in the intrinsic regime indicates similar carrier mobilities to SiGe. Large positive and negative Seebeck coefficient values were also observed at room temperature suggesting the electron and hole mobilities are similar.

### III. CONCLUSIONS AND FUTURE PLANS

This program has shown that the ruthenium and osmium silicides are low thermal conductivity, band-type semiconductors similar to SiGe, with band gaps sufficiently large to limit excessive intrinsic behavior at the highest temperatures. Alloying with germanium and doping with boron and phosphorus, can be expected to result in high figure of merit materials, just as similar techniques applied to pure silicon resulted in the SiGe alloys in use today. The us

### III. CONCLUSIONS AND FUTURE PLANS

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The current investigation must be supplemented by doping and alloying experiments. More importantly, development of high temperature Seebeck measurement techniques suitable to small samples must be completed before any reliable performance evaluations can be made. Future plans consist of

the following activities:

- 1) complete development of high temperature Seebeck measurement capability suitable to small sample sizes;
- 2) investigate sample preparation techniques including arc-melting, zone-melting and annealing to improve sample homogeneity;
- 3) investigate the use of boron and phosphorous as doping agents to control the carrier concentration and optimize the electrical properties; and
- 4) investigate alloys of the compounds  $\text{Ru}_2\text{Si}_3$ ,  $\text{Os}_2\text{Si}_3$  and the germanium analogs to control the thermal conductivity and optimize the figure of merit.

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FIGURE CAPTIONS

FIGURE 1: Thermal conductivity of several transition metal silicides prepared in this study. SiGe is shown for comparison.

FIGURE 2: Thermal conductivity of Ru<sub>2</sub>Si<sub>3</sub>-type samples as a function of temperature. SiGe is shown for comparison.

FIGURE 3: Electrical Resistivity as a function of inverse temperature for undoped samples of Ru<sub>2</sub>Si<sub>3</sub>, Os<sub>2</sub>Si<sub>3</sub>, and SiGe.

Table 2: Physical properties of some silicon base compounds.  
 Calculated values are based on the crystal structure identified in the  
 X-ray diffraction work summarized in Table 1.

Sample Number	Nominal Composition	# atoms per Formula Unit	# Formula Units per Cell	Formula Weight grams	Density Ideal g/cc	Density Measured g/cc	Seebeck Coef		Carrier Conc. 10E20/cc	Hall Mobility cm <sup>2</sup> /V-s	Electric Resistiv mohm-cm	Unit Cell Volume A <sup>3</sup>	Cp Debye J/K-cm <sup>3</sup>	Cp Debye Measur J/K-g	Cp J/K-g	Minimum Thermal Conductivity W/cm-K
							Low	High								
	Si	1	8	28.09	2.30	2.33						161.90	2.05	0.888	0.976	
	Si <sub>0.8</sub> Ge <sub>0.2</sub>	1	8	36.99	3.00	3.00						163.86	2.02	0.674	0.700	0.041
50	CrSi <sub>2</sub>	3	4	108.17	5.75	5.07	102		6.65	12.7	0.740 *	124.95	3.98	0.691	0.688	0.087
55	Ru <sub>2</sub> Si <sub>3</sub>	5	2	287.66	6.99	7.61	-256	201			*	136.70	3.03	0.433		
56	RuSi <sub>2</sub>	5	2	287.66	6.99	6.84	-30	54			11.62 *	136.70	3.03	0.433		0.012
57	Ru <sub>2</sub> Si <sub>3</sub>					7.06	-158	164					3.03			0.027
58	Os <sub>2</sub> Si <sub>3</sub>	5	2	464.66	11.08	10.80	20	232			10240	139.32	2.97	0.268		0.031
59	Ir <sub>3</sub> Si <sub>5</sub>					10.45	3.4	287								
60	Rh <sub>3</sub> Si <sub>5</sub>					7.81	-3.7	-0.7			0.202					
61	BeSi <sub>2</sub>	3	2	242.37	10.71	9.39			0.105	54.03	11.03 *	75.13	3.31	0.309		
62	OsSi <sub>2</sub>	5	2	464.66	11.08	8.52	200	289				139.32	2.97	0.268		
63	BeSi <sub>2</sub>	3	2	242.37	10.71	6.68	112	176			*	75.13	3.31	0.309		0.128
64	RuSi <sub>1.8</sub> Ge <sub>0.2</sub>	5	2	287.66	7.01						18320	136.33	3.04	0.433		0.025

\* - Literature Values

Table 1: Transition metal silicides prepared by reaction sintering.

Sample Number	Nominal Composition	XRD Major Phase	Comments
50	CrSi <sub>2</sub>	CrSi <sub>2</sub>	Incongruent melting indicated in DTA
55	Ru <sub>2</sub> Si <sub>3</sub>	Ru <sub>2</sub> Si <sub>3</sub>	Trace of second phase indicated by metallograph
56	RuSi <sub>2</sub>	Ru <sub>2</sub> Si <sub>3</sub>	No second phase detected
57	Ru <sub>2</sub> Si <sub>3</sub>		
58	Os <sub>2</sub> Si <sub>3</sub>	Os <sub>2</sub> Si <sub>3</sub>	No second phase detected
59	Ir <sub>3</sub> Si <sub>5</sub>	Multiphase	Significant material loss during pressing
60	Rh <sub>3</sub> Si <sub>5</sub>	Multiphase	Most material lost during pressing
61	ReSi <sub>2</sub>	ReSi <sub>2</sub>	Si (trace)
62	OsSi <sub>2</sub>	Os <sub>2</sub> Si <sub>3</sub>	a
63	ReSi <sub>2</sub>	-	
64	RuSi <sub>1.8</sub> Ge <sub>0.2</sub> Ru <sub>2</sub> Si <sub>3</sub>		No second phase detected

a - A trace of second phase detected. Possibly OsSi<sub>2</sub>, but not Si

Table XXX: CANDIDATE TRANSITION METAL SILICIDES FOR THERMOELECTRIC APPLICATIONS  
EXTREME VALUES OF THERMOELECTRIC PROPERTIES SUMMARIZED FROM LITERATURE REFERENCES

Promising Candidate Systems	Compound #	Name	Phase Diagram	Nearest Ge Compound (Si,Ge)	Temp. Stability Range(1) (C)	Lowest Thermal Conductivity mW/cm-K	Lowest Electrical Resistivity mohm-cm	Highest Band Seebeck Gap microV/KeV	Estimated Carrier Mobility cm <sup>2</sup> /V-s	Other Reference
-->	1	CrSi <sub>2</sub>	2,2	Cr <sub>11</sub> Ge <sub>19</sub>	1475 M	424	0.334	20012	1.31	20.0 6,14
	2	ReSi	2,2	ReGe	1880 Pr		0.3515	351		18.7 15
-->	3	ReSi <sub>2</sub>	2,2	Re <sub>3</sub> Ge <sub>7</sub>	1980 C	555	25	1741	0.121	435.0 15
	4	FeSi	2,2	FeGe	1410 C	981	0.261	91	0.051	-1.5 6,15
	5	a-FeSi <sub>2</sub>	1,2	FeGe <sub>2</sub>	1220 C	1221	0.451	251	0.81	6,15,16
	6	b-FeSi <sub>2</sub>	1,2	FeGe <sub>2</sub>	986 PD	3619	6671	20016		19
-->	7	Ru <sub>2</sub> Si <sub>3</sub>	2,21	-	1800				1.025	18
-->	8	Os <sub>2</sub> Si <sub>3</sub>	21,-	OsGe <sub>2</sub>						18,24
-->	9	OsSi <sub>2</sub>	-, -	OsGe <sub>2</sub>	1730		1020	38020	1.820	
-->	10	Rh <sub>2</sub> Si <sub>3</sub>	-,23	-						
-->	11	RhSi <sub>2</sub>	-,23	-						
-->	12	Ir <sub>3</sub> Si <sub>5</sub>	-, -	Ir <sub>3</sub> Ge <sub>7</sub>					1.025	
-->	13	IrSi <sub>2</sub>	-, -	Ir <sub>3</sub> Ge <sub>7</sub>		4617	0.6817	4517		24
-->	14	IrSi <sub>3</sub>	-, -	Ir <sub>3</sub> Ge <sub>7</sub>	>1500 M					
	15	a-LaSi <sub>2</sub>	-,2	-	1600 PI		0.231	-51	0.191	0.6
	16	b-LaSi <sub>2</sub>	-,2	-	1520 M		Semi?			
	17	USi <sub>3</sub>	-	-		130	0.2517	2917		

C=Congruent melting  
Pr=Peritectic-reaction melting  
M=Melting (no indication of type)  
PD=Peritectoid decomposition  
PI=Polymorphic inversion

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No.	Compound Name	Phase Diagram	Nearest Temp. Ge Compound	Lowes Stability Range(1) (C)	Butecic (C) (a/o)	Crystal Structure Ref1,4,18	Lowest Thermal Conductivity nW/cm-Kohn	Lowest Electrical Resistivity cm-microV/KeV	Highest Seebeck Coefficient microV/KeV	Standard Carrier Concentration (estimated) 1020/ccm2/v-s1000/K	Carrier Mobility of Figure Merit	Other Hall Reference	HoRefConstant 104 cm3/C	Nature Range of Conversion (C)	M.P	
																Estimated
1	Mg2Si	2,2	Mg2Ge	1100 C	945. 53	Si2 CaF2	Semi1	2000	10.771		6	Activated1	C			
2	Ca2Si	1,2	Ca2Ge	910 Pr		PbCl2			1.91				Pr			
3	Ca2Si	1,2	Ca2Ge	910 Pr		Cubic							Y 1 Pr			
4	CaSi	1,2	CaGe	1245 C		TlI							C			
5	CaSi2	1,2	CaGe2	1020 Pr		CaSi2(I)							Pr			
6	CaSi2	1,2	CaGe2	1020 Pr		CaSi2(II)							Pr			
7	Sr2Si	1,2	Sr2Ge	1010 M									M			
8	SrSi	1,2	SrGe	1140 C		TlI							C			
9	Sr2Si3	?				a-ThSi2										
10	SrSi2	1,2	SrGe2	1150 C		SrSi2							C			
11	BaSi	1,2	BaGe	840 Pr		TlI							Pr			
12	BaSi2	1,2	BaGe2	1180 C		AlB2	15.51251	6001	0.481		0.931		C			
13	BaSi2	1,2	BaGe2	1180 C		BaSi2							C			
14	CrSi	2,2	CrGe	1413 Pr	1305 87	Si2 FeSi	1331	0.121	51	-13601	-0.4	0.001	6,14	-0.461	Pr	1550
15	CrSi2	2,2	Cr11Ge19	1475 M	1305 87	Si2 CrSi2	424	0.334	200121.31	9.31	20.0	2.857	6,14	66.51	M	1550
16	a-MoSi2	2,21		1850 PI	1414 98	Si2 CrSi2	4851	0.0225	-31	49.21	60.0	0.001		12.71	PI	1980
17	b-MoSi2	2,21		2030 M		MoSi2									M	
18	WSi2	1,2	W2Ge3	2160 C	1440 99	Si3 CrSi2		0.0135	0.21	0.741	6700.0		8411		C	2165
19	WSi2	1,2	W2Ge3			MoSi2										
20	MnSi	2,22		1275 C	1142 66	Si2 FeSi	426	0.251	1021			0.956	6,13,15		C	
21	Mn11Si192,22			1152 C	1142 66	Si2 Mn11Si19	17.910.259					0.000		Y 2 C		
22	Mn4Si7	2,22			1142 66	Si2 Mn4Si7	2510	1.827	1047			0.238				
23	MnSi2	?,22			1142 66	Si2		1.836	21512				6,13,15			
24	ReSi	2,2		1880 Pr	1380 90	Si2 FeSi		0.3515	351	9.51	18.7		15	65.41	Pr	
25	ReSi2	2,2	Re3Ge7	1980 C	1380 90	Si2 MoSi2	555	25	1741	0.1210.071	435.0	0.280	15	87001	C	1980
26	FeSi	2,2	FeGe	1410 C		FeSi	981	0.261	91	0.051-1561	-1.5	0.003	6,15	-41	Y 2 C	
27	FeSi1.15?	-				Lebeaunte										
28	a-FeSi2	1,2	FeGe2	1220 C	1208 73	Si3 a-FeSi2	1221	0.451	251	0.81		0.010	6,15,16		C	1220
29	b-FeSi2	1,2	FeGe2	986 PD		b-FeSi2	3619	6671	20016	-21001		0.500	19	-0.31	PD	
30	Ru2Si3	2,21		1800	1370 83	Si3 Ru2Si3				1.026			18			1800
31	Os2Si3	21,-			1357 90	Si20Ru2Si3							18,24			
32	OsSi2	-,-		1730	1357 90	Si20b-FeSi2		1020	380201.820							1730
33	OsSi2.4	-,-			1357 90	Si20OsGe2										
34	CoSi	1,2	CoGe	1460		FeSi	1431	0.0861	-1487	-3611	-2.0	1.780	6	-1.731	Y	1460
35	CoSi2	1,2	CoGe2	1326	1195 23	Si3 CaF2	3801	0.011	-377	2471	18.0	0.260	6,15	2.531		1326
36	Rh4Si5	-,-,23				Rh4Si5										
37	Rh3Si4	-,-,23				Rh3Si4										
38	Rh2Si3	-,-,23														
39	RhSi2	-,-,23														
40	Ir4Si5	-,-				Rh4Si5										
41	Ir3Si4	-,-				Rh3Si4										
42	Ir3Si5	-,-								1.026						
42	Ir2Si3	-,-				Monoclini										
43	IrSi2	-,-	Ir3Ge7				4617	0.6817	4517				24			
44	IrSi3	-,-		>1500 M		Na3As									M	>1500
45	a-LaSi2	-,-,2		-160 PI		a-ThSi2		0.231	-51	0.191-4171	0.6		-1.51		PI	
46	b-LaSi2	-,-,2		1520 M		a-GdSi2		Semi?1							M	
47	USi3					Cu3Au	130	0.2517	2917							

C=Congruent melting  
Pr=Peritectic-reaction melting  
M=Melting (no indication of type)  
PD=Peritectoid decomposition  
PI=Polymorphic inversion  
D=Decomposition  
S=Sublimation  
DS=Dissociation

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