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Review

Exploration of new superconductors and functional materials, and fabrication of superconducting tapes and wires of iron pnictides

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Abstract

This review shows the highlights of a 4-year-long research project supported by the Japanese Government to explore new superconducting materials and relevant functional materials. The project found several tens of new superconductors by examining ~1000 materials, each of which was chosen by Japanese experts with a background in solid state chemistry. This review summarizes the major achievements of the project in newly found superconducting materials, and the fabrication wires and tapes of iron-based superconductors; it incorporates a list of ~700 unsuccessful materials examined for superconductivity in the project. In addition, described are new functional materials and functionalities discovered during the project.

Keywords: superconductivity, iron pnictide, new superconductors, superconducting wire, superconducting tape, functional material, powder in tube

1. Introduction

Since the discovery of superconductivity by Heike Kamerling Onnes in 1911 [1], it has been the dream of researchers to realize a room temperature superconductor. Although the fundamental theoretical framework for superconductivity was

Table 2. Exploration of new superconductors in this project. (a) Materials which exhibited superconductivity. (b) Materials which exhibited no superconductivity.

(a) Materials which exhibited superconductivity

: noted in this review, (HP); synthesized using high pressure technique

IBSC			
	Material	T_c (K)	Comment
1	$SmFeAsO_{1-x}H_x$ [9]	56	large solubility limit of dopant H^- (HP)
2	$NdFeAsO_{1-x}H_x$ [9]	54	large solubility limit of dopant H^- (HP)
3	$CeFeAsO_{1-x}H_x$ [10]	48	large solubility limit of dopant H^- (HP)
4	$LaFeAsO_{1-x}H_x$ [11]	36	two T_c domes (HP)
5	$SmFeAs_{1-x}P_xO_{1-y}H_z$ [12]	<56	T_c decreased by replacing with P (HP)
6	$LaFe_{1-x}Zn_xAsO_{1-y}H_z$ [13]	<36	T_c decreased by replacing with Zn (HP)
7	$LaFeAsO_{0.85}H_x$ (x =0-0.85) [14]	35	indirect electron doping by V_O and H^-(HP)
8	$LaFeAsO_{1-x}$ [15]	22	indirect electron doping by V_O (HP)
9	$CaFe_{1-x}Co_xAsH$ [16]	23	direct electron doping into CaFeAsH (HP)
10	$Ca_{1-x}La_xFeAsH$ [17]	47	indirect electron doping into CaFeAsH (HP)
11	$Ca_{1-x}Sm_xFeAsH$ [17]	46	indirect electron doping into CaFeAsH (HP)
12	$CaFeAsF_{1-x}$ [18]	27	indirect electron doping (HP)
13	$Sr_{1-x}La_xFe_2As_2$ [19]	23	indirect electron doping (HP)
14	$(Ba,La)Fe_2As_2$ [20]	22.4	indirect electron doping (thin film)
15	$(Ba,Ce)Fe_2As_2$ [21]	13.5	indirect electron doping (thin film)
16	$(Ba,Pr)Fe_2As_2$ [21]	6.1	indirect electron doping (thin film)
17	$(Ba,Nd)Fe_2As_2$ [21]	5.8	indirect electron doping (thin film)
18	$(Sr,La)Fe_2As_2$ [22]	20	indirect electron doping (thin film)
19	$(Ca,La)Fe_2(As,P)_2$ [23]	45	bulk SC achieved by co-doping of La and P
20	$Ba(Fe,Pt)_2As_2$ [24]	24	dome-like relation between T_c and dopant Pt
21	$(Ca,La)FeAs_2$ [25]	34	new type IBSC: 112
22	$(Ca,La)Fe(As,Sb)_2$ [26]	43	increase in T_c by co-doping
23	$(Ca,RE)Fe(As,Sb)_2$ [27]	47	highest T_c in 112 type (RE=La, Ce, Pr, Nd)
24	$Ca_{10}(Ir_4As_8)(Fe_2As_2)_5$ [28]	16	analogous to $Ca_{10}(Pt_4As_8)(Fe_{2-x}Pt_xAs_2)_5$
25	$Na_{0.65}Fe_{1.93}Se_2$ [29]	37	intercalating Na into FeSe
26	$(Na,NH_3)Fe_2Se_2$ [29]	42	co-intercalating Na and NH_3 into FeSe
27	$LaFeAs(O,C_2)$	27	electron doping by C_2 (HP)
Analogous structure to IBSC			
	Material	T_c (K)	Comment
28	$SrAl_2Si_2$	4.6	IBSC 122 type structure (HP)
29	NbSiAs [30]	8.2	square net of Si
30	$BaTi_2Sb_2O$ [31]	3	square net of Ti (measured under HP)
31	$BaTi_2(Sb_{1-x}Bi_x)_2O$ [32]	1.2	square net of Ti, SC by doping of isovalent ion.
32	$BaTi_2(Sb_{1-x}Sn_x)_2O$ [33]	2.5	square net of Ti, SC by doping of aliovalent ion
33	$La(Co_{1-x}Fe_x)_2B_2$ [34]	4	square net of Co
34	$(La_{1-x}Y_x)Co_2B_2$ [34]	4	square net of Co
35	$BaNi_2(As,P)_2$ [35]	3.3	analogous to 122 type of IBSC
36	$Ba(Ni,Cu)_2As_2$	3.3	analogous to 122 type of IBSC
37	$LnNiAsO_{1-x}H_x$ [36]	3.7	H doping to LnNiAsO (Ln=La-Nd) (HP)
38	$NdNi_{0.64}Bi_2$	4	square net of Ni and Bi
39	YNi_xBi_2 [37]	4	square net of Ni and Bi
40	$LaNi_xBi_2$ [37]	4	square net of Ni and Bi
41	$CeNi_xBi_2$ [37]	4	square net of Ni and Bi
42	LaNiBN [38]	4.1	square net of Ni (HP)
43	CaNiBN [38]	2.2	square net of Ni (HP)
44	LaPtBN [38]	6.7	square net of Pt (HP)
45	$La_3Ni_2B_2N_3$ [38]	15	square net of Ni (HP)
46	$LaPd_2As_2$ [39]	1	collapsed 122 structure
47	$LaPd_2Sb_2$ [40]	1.4	$CaBe_2Ge_2$ structure
48	$SrPt_2Sb_2$ [41]	2.1	$CaBe_2Ge_2$ structure
49	$BaPt_2Sb_2$ [42]	1.9	$CaBe_2Ge_2$ structure
50	$SrPd_2Bi_2$	2.2	$CaBe_2Ge_2$ structure
51	$CaPd_2Bi_2$	2.6	$CaBe_2Ge_2$ structure
52	$SrPt_2Bi_2$	2.6	$CaBe_2Ge_2$ structure
53	La_2Sb [43]	5	square net of La
Other layered structure			
	Material	T_c (K)	Comment
54	$La_3Ru_4B_6$ [44]	3.2	homologous structure
55	CrNbN	11	Cr layer (multiphase)

Table 2. (Continued.)

56	$Ca_2Al_2Si_4$ [45]	6.4	high pres. phase of Ca-Al-Si (HP)
57	Mg_4AlSi_3 [46]	5.2	new layered structure (HP)
58	$Si(Si_{1-x}Ni_x)_2$	3	Si layer
59	$Ba(Si_{1-x}Cu_x)_2$	3	Si layer
60	$LaSi_2H_{0.03}$	3	H doping to $ThSi_2$ structure (T_c increased)
61	$BaGe_2H_{0.35}$	4	H doping to $ThSi_2$ structure (T_c decreased)
62	$LaGe_{1.7}$	2	$ThSi_2$ structure with cage formed by sp^2 orbital
63	$Zr_2Ru_2Si_4$ [47]	5.7	analogous structure to ZrRuP superconductor
64	MgPtSi [48]	2.5	honeycomb lattice
65	$SrAuSi_3$ [49]	1.54	noncentrosymmetric structure
66	Li_2IrSi_3 [50]	3.8	noncentrosymmetric structure
67	LaIr*Pn* [51]	5.3	noncentrosymmetric structure (*Pn* = P and As)
68	LaRhP [51]	2.5	noncentrosymmetric structure
69	$Bi_4O_4S_3$ [52]	4.5	double BiS plane
70	$LnO_{1-x}F_xBiS_2$ (*Ln*=La,Ce,Nd) [53]	3 (10)	triple BiS plane. (measured under HP)
71	KMo_6Se_8	9	new Chevrel phase compound
72	Nb_3Ir_3O	10.5	O doped Mn_5Si_3 structure
73	$Ba_3(Bi_{1-x}Sb_x)_3$ [54]	4.3	square/honeycomb lattice
74	Y_2CrC_2	1.5	Cr/C layer
75	$SrNiSn_3$	5	noncentrosymmetric structure
76	β-ZrNF	15	ion exchange of β-ZrNCl by F
77	$Zr_5(N_4O)F_6$	2-5	low SVF
Intercalation to layered structure			
	Material	T_c (K)	Comment
78	TiNCl← amines [55]	17	intercalation of long alkylene diamine →high T_c
79	TiNCl← alkali metal (Li-Rb) [56]	18.0	highest T_c by Na intercalation
80	TiNCl← alkali metal + solvent [56]	10.5	highest T_c by Na+THF co-intercalation
81	TiNBr← alkali metal [57]	17.2	highest T_c by K intercalation
82	ZrNCl← K + THF, PC [58]	16	highest T_c by K+THF co-intercalation
83	α-ZrNCl← alkali metal	10	superconductivity of α-type structure
84	HfNCl← *AE*(Ca-Ba), solvent [59]	26	highest T_c by Ca+THF co-intercalation
85	*M*NCl←Yb, Eu (*M*: Zr, Hf) [60]	24.3	highest T_c by Eu+NH_3 co-intercalation into HfNCl
86	Hf_2N_2O←Li	4.6	La_2O_3 type structure
Chalcogenides			
	Material	T_c (K)	Comment
87	1T-TaS_2	3	suppressing CDW (HP)
88	$AuTe_2$ [61]	2.3	SC by dissociation of Te_2 dimer (CdI_2 structure)
89	$(Au,Pt)Te_2$ [62]	4	SC by dissociation of Te_2 dimer (CdI_2 structure)
90	$(Au,Pd)Te_2$	3	SC by dissociation of Te_2 dimer (CdI_2 structure)
91	$(Ir,Pt)Te_2$ [63]	3.1	SC by dissolving of orbital ordering (CdI_2 structure)
92	Cu_xIrTe_2	3	SC by dissolving of orbital ordering (CdI_2 structure)
93	$(Ir,Rh)Te_2$ [64]	2.6	SC by dissolving of orbital ordering (CdI_2 structure)
94	Ir_xSe_2 [65]	8	pyrite structure (HP)
95	$Ir_{1-x}Rh_xSe_2$ [66]	10	pyrite structure (Rh doping) (HP)
96	$Ir_{0.95-x}Rh_xTe_2$ [67]	4.6	pyrite structure (small effect of Rh doping) (HP)
Others			
	Material	T_c (K)	Comment
97	$NbBe_3$	2.6	Laves phase
98	MoC_{1-x} [68]	12	formed $MoC_{0.681}$ under 6 GPa
99	$MoC_{0.75}$ [69]	13	formed $MoC_{0.75}$ under 17 GPa
100	YFe_2SiC	3.5	having YFe_2Si framework
101	ScC_xO_x	8	having C-C bonding (low SVF)
102	$Ti_{4-x}N_3$	<5	decomposition of TiNCl in NH_3
103	$Zr_{4-x}N_3$	<10	decomposition of ZrNCl in NH_3
104	$Hf_{4-x}N_3$	<6	decomposition of HfNCl in NH_3
105	$Mg(Mg_{1-x}Al_x)Si$ [70]	6.2	anticotunnite or TiNiSi structure (HP)
106	$Ca(Al, Si)_2$ [71]	2.6	Laves phase (HP)
107	Nb_4MSi (M=Ni, Co, Fe) [72]	7.7	2 dimensional network of Nb
108	$Ba_3Ir_4Ge_{16}$ [73]	6.1	aving cage structure
109	$Ba_4Ir_8Ge_{28}$ [73]	3.2	having cage structure
110	Ca_2InN [74]	0.6	doping of In^{-1} into Ca_2N
111	SnAs	2	hole in As4*p* orbital
112	$CuZr_2$	1	
113	$HfZr_2$	1	

Table 2. (Continued.)

(b) Materials which exhibited no superconductivity

: possible to obtain the target phase, : impossible to obtain the target phase

IBSC (Square net of Fe)				
MgFeAsH	SrFeAsH	BaFeAsH	EuFeAsH	MgFePH
CaFePH	$CaFeAsF_{1-x}$	$CaFeAsF_{1-x}O_x$	$CaFeAsF_{1-y}H_x$ [9]	$Ca_{1-x}La_xFeAsF$
$Sr_{1-x}La_xFeAsF$	$Ca_{1-x}Na_xFeAsH$	LaFeAsO:N	$CaFeAsH_{1-x}O_x$	LaFeOSb
CaFeOSe	SrFeOSe	KFeSeF	LaFeSiF	$Ba(Fe,Re)_2As_2$
$Ca(Fe,Au)_2As_2$ (thin film)	$Ca(Fe,Mg)_2As_2$	$Ca(Fe,Al)_2As_2$	$Ca(Fe,Pt)_2As_2$ [75]	$Ca(Fe,Ru)_2As_2$
$(Ca,La)Fe_2As_2$	$YFe_{2-x}Co_xGe_2$	$BaFe_{2-x}Zn_xAs_2$	$BaFe_2Sb_2$	$BaFe_2Se_2$
$(Fe,Mn)_2AlB_2$	$(Fe,Co)_2AlB_2$	$(Fe,Ni)_2AlB_2$	$(Fe,Cr)_2AlB_2$	$ZrFe_2Si_2$
$ZrFe_2B_2$	$LuFe_{2-x}Si_2$	$YFe_{2-x}Si_2$	$TlFe_{2-x}Co_xSe_2$	$TlFe_{2-x}Ni_xSe_2$
$Tl_{1-x}Fe_2Se_2$	$MgFe_2As_2$	$CdFe_2As_2$	YFe_2B_2	$Fe_{2-x}Cu_xAs$
(Fe,Pt)Se	Fe(Te,As)	Fe(Se,As)	$FeP_{0.5}X_{0.5}0.5$ (X = Cl, Br)	$FeSe_{1-x}X_x$ (X = P, Cl)
$FeSb_{1-x}$	La-$Ca_{10}(Ir_4As_8)(Fe_2As_2)_5$	Ge- $Ca_{10}(Ir_4As_8)(Fe_2As_2)_5$	P- $Ca_{10}(Ir_4As_8)(Fe_2As_2)_5$	Re- $Ca_{10}(Ir_3As_8)(Fe_2As_2)_5$
K- $Ca_{10}(Ir_4As_8)(Fe_2As_2)_5$	Sr- $Ca_{10}(Ir_4As_8)(Fe_2As_2)_5$	Ba- $Ca_{10}(Ir_4As_8)(Fe_2As_2)_5$	$Ca_{10}(M_4As_8)(Fe_2As_2)_5$ (M=Pd,Rh)	$Ba_{10}(Pt_4As_8)(Fe_2As_2)_5$
$Sr_{10}(Pt_4As_8)(Fe_2As_2)_5$	$Ca_{10}Pt_{5.8}Fe_{8.2}Sb_{18}$	Ba_2InO_3FeAs	Sr_2InO_3FeAs	Sr_2FeO_3FeAs
Ba_2FeO_3FeAs	$Sr_4V_2O_6Fe_2As_2$	$Bi_2SrFe_2O_6Se_2$	$La_2O_2Fe_4As_4$	$Ca_2F_2Fe_4As_4$
$La_2O_2Fe_2(S_{1-x}F_x)_2$	$La_2O_2Fe_2(Se_{1-x}F_x)_2$	$La_2O_2Fe_2(Se_{1-x}As_x)_2$	$La_2O_2Fe_2(Se_{1-x}Ge_x)_2$	$La_2O_2(Fe_{1-x}Co_x)_2Se$
$La_2O_2(Fe_{1-x}Mn_x)_2Se$	$NdFe_4Sb_2$	$Fe_{1-x}Cu_xAs_{0.5}$	EuFeAsO$_{1-x}$	$Fe_{1-x}Si_2$
$(Fe_{1-x}Mn_x)_{1-y}Si_2$	$(Fe_{1-x}Co_x)_{1-y}Si_2$	$(Fe_{1-x}Mo_x)_{1-y}Si_2$	AgFeAs	$La(Fe_{1-x}Co_x)_2Si_2$
$Fe_{0.82}(Si_{1-y}Ge_y)_2$	$RFeC_2$	Sc(Fe,Co)C_2	Sc(Fe,Ni)C_2	La(Fe,Co)Si_2
La(Fe,Mn)Si_2	$LaFe_{0.5}Sb_2$	$CaFe_4As_3$	$CaFe_3AgAs_3$	$CaFe_3CuAs_3$
$CaFe_3LiAs_3$	$La_3O_6Fe_4As_3$	Fe(Se,As)$_2$	(Fe,Mn)As_2	(Fe,Ru)As_2
(Fe,Rh)As_2	(Fe,Co)As_2	(Fe,Ni)As_2	(Fe,Pd)As_2	$La_{1-x}RE_xCu_2O_{6-y}Fe_2As_2$
$Sr_3Fe_2Cu_2Se_2O_3$	$Sr_{2.6}K_{0.4}Fe_2Cu_2Se_2O_5$	$La_3O_4Fe_4As_4$	$Ca_3Fe_4As_4F_2$	Ca_2FeOsO_6
$Ba_{1-x}K_xFe_2X$ (X = S, Se)	$NaFe_2O_4$	$BaFe_{2-x}Co_xSe_2$	$Tl_{1-x}Ba_xFeSe_2$	$La_2Fe_2Se_2O_{3-x}H_x$
$La_2Fe_2S_2O_{3-x}H_x$	CaBaFe2Pn2O (Pn = As Sb, Bi),	SrFe$_2$*Pn*$_2$O (*Pn* = As, Sb, Bi)	BaFe$_2$*Pn*$_2$O (*Pn* = As, Sb, Bi)	$BaFe_2Se_2O$
t-FeS				
Analogous structure to IBSC material				
Square net of transition metal elements		BaSc$_2$*Pn*$_2$O (*Pn*=As, Sb, Bi)	$SrTi_2As_2O$	$BaTi_2(As,Sb)_2O$ [31]
$EuTi_2As_2O$	$BaTi_2Sb_2O$	$(SrF)_2Ti_2Bi_2O$ [76]	$(SrF)_2Ti_2(Sb_{1-x}Bi_x)_2O$	$Zr_2Ti_2As_2H$
$Zr_2Ti_2Pn_2H$ (*Pn* = Sb, Bi)	$ZrTiPn$ (*Pn* = Sb, Bi)	ZrTiAs	BaV_2Ge_2O	BaV_2Sn_2O
BaV$_2$*Pn*$_2$O (*Pn* = As, Sb, Bi)	*Ln*CrAsO (*Ln*=La-Nd, Sm) [77]	SrCrAsF	EuCrAsF	$La_{1-x}CaMnAsO_{1-y}F_y$
$Ce_{1-x}CaMnAsO_{1-y}F_y$	$Sm_{1-x}CaMnAsO_{1-y}F_y$	SrMnAsF	BaMnAsF	EuMnAsF
$LaMnAsO_{1-x}H_x$	$CeMnAsO_{1-x}H_x$	$DyMnAsO_{1-x}H_x$	$LaZn_{1-y}Mn_xAsO_{0.73}$	$CaMn_2As_2$
$CaMn_2Sb_2$	$CaMnBi_2$	$(Ca,La)Mn_2Sb_2$	$BaMn_2As_2$	$(Ba,K)Mn_2As_2$
$BaMnRuAs_2$	$BaMnFeAs_2$	$BaMnCoAs_2$	$BaMnRhAs_2$	$BaMnIrAs_2$
$BaMnBi_2$	$LaMn_2Si_2$	$Sr(Mn,Fe)_2P_2$	$Sr(Mn,Cr)_2P_2$	$Sr(Mn,Al)_2P_2$
$Sr(Mn,Zn)_2P_2$	$(Ca,Eu)Mn_2P_2$	$La_2O_2Mn_2Te_2O$	CaMn$_2$*Pn*$_2$O (*Pn* = As, Sb, Bi)	SrMn2*Pn*2O (*Pn* = As, Sb, Bi)
BaMn$_2$*Pn*$_2$O (*Pn* = As, Sb, Bi)	$BaMn_2Se_2O$	$Ca_{10}(Pt_4As_8)(Mn_{2-x}Pt_xAs_2)_5$	$LaCoAsO_{1-x}H_x$	(Ca,La)$CoAs_2$
$(Sr_{1-x}Ca_x)Co_2Ge_2$	$BaCo_2Ge_2$	YCo_2B_2	YCo_2Ge_2	$LaCo_{0.6}Sb_2$
$LaCo_2Si_2$	$La(Co_{1-x}Ni_x)_2Si_2$	$LaCo_2(B_{1-x}Si_x)_2$ [37]	$LaCo_2Ge_2$	$NdCo_2Sb_2$
$GdCo_2B_2$	$LaCo_2B_2C_x$	$ZrCo_2Si_2$	$HfCo_2Si_2$	$HfCo_2Ge_2$
CaCo$_2$*Pn*$_2$O (*Pn* = As, Sb, Bi)	SrCo$_2$*Pn*$_2$O (*Pn* = As, Sb, Bi)	BaCo$_2$*Pn*$_2$O (*Pn* = As, Sb, Bi)	$Ca_{10}(Pt_4As_8)(Co_{2-x}Pt_xAs_2)_5$	(Ca,La)$NiAs_2$
CaNiAsH	$Ba_{1-x}La_xNi_2As_2$	MgNiGe [78]	$CaNi_{1-x}Mn_xGe$ [79]	$CaNi_{1-x}Mn_xGeH$ [80]
Y_3NiSi_3	LaNiAs	La_3NiSi_3	$CeNiBiO_{1-x}$	$ZrNi_{0.75}P$
$ZrNi_{0.75}As$	KNi_2Se_2	$ZrNi_2Si_2$	RhNiP	$GdNi_2Bi_2$
$Ni_3(Te_{1-x}Se_x)_2$	CaNi$_2$*Pn*$_2$O (*Pn* = As, Sb, Bi)	SrNi$_2$*Pn*$_2$O (*Pn* = As, Sb, Bi)	BaNi$_2$*Pn*$_2$O (*Pn* = As, Sb, Bi)	$Ca_{10}(Pt_4As_8)(Ni_{2-x}Pt_xAs_2)_5$
Cu_2As	Cu_2Sb	MgCuAs	$Ca_2Cu_6P_5$	$BaCu_{1.8}As_2$
$BaCu_2As_2$	$Ba_2Cu_2P_4$	$BaCu_6As_2$	YCuSb$_2$	YCuAs$_2$
CeCuPO	$GdCu_{1.25}P_{1.75}$	$ZrCu_2P_2$	$ZrCu_2As_2$	ZrCuSiAs
$HfCu_2P_2$	$Hf_{0.5}Cu_{1-x}Mn_xP$	$HfCuSi_2$	$HfCuGe_2$	BiOCuS
Ca$_2$Cu$_2$*Pn*$_2$O (*Pn* = As, Sb, Bi)	Sr$_2$Cu$_2$*Pn*$_2$O (*Pn* = As, Sb, Bi)	Ba$_2$Cu$_2$*Pn*$_2$O (*Pn* = As, Sb, Bi)	$La_3(O,F)_2Cu_4As_4$	$Bi_2LnO_6Cu_{2-x}Fe_xSe_2$ (*Ln*=lamtanide elements)
$BaZnBi_2$	$K_2NbO_{3-x}F_{1-x}$	(Ca,La)$RuAs_2$	$La_3Ru_2B_2N_3$ [38]	LaRuBN [38]

Table 2. (Continued.)

LaRhBN [38]	(La, Sr)Pd_2As_2	LaIrBN [38]	(Sr,K)Pt_2As_2	(Ca,La)$PtAs_2$
$[Sr_2MO_2][Ti_2As_2O]$, $[Sr_3M_2O_3][Ti_2As_2O]$ (M = Cr, Mn, Fe, Co, Ni, Cu)				
Square net of traditional elements		TiSiAs	$SrGa_2$	$BaGa_2$
NbGeAs	TaGeAs	$BaNiSn_3$	$LaMn_xSb_2$	La_2O_2Sb
Ce_2O_2Sb	$CeAgSb_2$	$Nd(Fe_{1-x}Co_x)_yAs_2$	La_2O_2Te	Y_2O_2Bi [81]
La_2O_2Bi [81]	$LaAgBi_2$	Ce_2O_2Bi [81]	$CeMn_xBi_2$	$CeZn_xBi_2$
$CeCu_xBi_2$	$CeAgBi_2$	Pr_2O_2Bi [81]	Nd_2O_2Bi [81]	Sm_2O_2Bi [81]
Eu_2O_2Bi	Gd_2O_2Bi	Er_2O_2Bi [81]	Yb_2O_2Bi	Y_5Si_3
La_5Si_3				
Other layered structure				
Honeycomb lattice		Mg_3PtSi	SrPdAs	(Sr,Y)PtAs
SrPtSb	BaPtSb	SrPdSb	YPtAs	LaPtSb
MgAgAs	SrCoP	SrNiP	SrCuP	SrPdP
SrAgP	SrIrP	SrAuSn	SrPtSn	SrAuSb
CaAuP	SrAuP	SrAuSi		
Mn_5Si_3 structure		V_5P_3	$V_5P_3N_x$	V_5As_3N
Nb_5Si_3	Ta_5Si_3	V_5Ge_3	$Nb_xGe_3N_x$	$Ta_5Ge_3N_x$
$Nb_5Ge_3C_x$	Zr_5Pb_3	Ta_5Ir_3O		
Mg_4AlSi_3 structure		$LiMg_4Si_3$	$NaMg_4Si_3$	$SrMg_4Si_3$
$BaMg_4Si_3$	YMg_4Si_3	$BaGe_3Mg_4$		
B, Si layer		CrB_2	MnB_2	FeB_2
ZnB_2	$SrNiSi_3$	$Ba(Si_{1-x}Zn_x)_2$	$Ba(Si_{1-x}Ni_x)_2$	$SiTe_2$
$SmGa_{2-x}Si_x$	CaCuSi	$YbGa_{0.9}Si_{1.1}$	$LaGa_{2-x}Si_x$	Lu_2AlSi_2
$CaSrSi_4$	$Ba_3Ga_{0.7}Si_{4.3}$	$Sr_{1-x}Na_xAl_2Si_2$	$Ba_{1-x}K_xAl_2Si_2$	$Ca_{1-x}Na_xAl_2Si_2$ [45]
$SrAl_{2-x}Si_{2+x}$	$BaSi_2$ (HP phase)			
Skutterdite structure		$Sr_xRhGe_{1.5}Se_{1.5}$	$Ba_xIrGe_{1.5}S_{1.5}$	$Ba_xIrGe_{1.5}Se_{1.5}$
$BaRh_2Ge_4S_6$ [82]	$BaRh_2Ge_4Se_6$ [82]	$BaIr_2Ge_4S_6$ [82]	$BaIr_2Ge_4Se_6$ [82]	$La_xIrGe_{1.5}S_{1.5}$
$La_xRhGe_{1.5}S_{1.5}$	$LaFe_4Bi_{12}$	$LaCo_4Bi_{12}$	$LaNi_4Bi_{12}$	$LaRu_4Bi_{12}$
$LaRh_4Bi_{12}$	$LaPd_4Bi_{12}$	$LaIr_4Bi_{12}$	$LaPt_4Bi_{12}$	
Others		$Y(Co,Fe)_4B_2$	$Y(Co,Ni)_4B_2$	Ca_2N [83]
Ca_xBN (film) [84]	$Ba(Ge_{1-x}Cu_x)_2$	Cr_2N	CuNCN	NbCrN
TiNF	Ti_2SbP	Zr_2SbP	Cr_2Ti	Cr_2Zr
Cr_2Hf	CrTaN	$NiTe_2$	$Ni(Te_{1-x}Se_x)_2$	$NaNiF_3$ [85]
SmNiAs	ZrAs	Ni_2Bi_3	$CaRuO_3$ [86]	$CaRhO_3$ [87]
$CaOsO_3$	$SrOsO_3$	$BaOsO_3$	$CaRhO_3$ (HP phase) [88]	MAN phase (M=Ti,V,Zr,Nb,Hf,Ta) (A=Si,P,S,Ga,In,Sn,Pb)
$La_3Ni_2O_7$	Sr_2SnO_{4-x}	Ba_2SnO_{4-x}	SnO: F	$Cu(Al,Mg)O_2$
$SrCr_2O_4$	$LaSrMnO_3H$	$(CuCl)LaNb_2O_{7-x}F_x$	Bi_2WO_6	$Ho_{0.25}Sr_{0.75}FeO_{2+d}$
$Na_2La_2Ti_3O_{10-x}$	$Sr_2TiO_4F_2$	$CaCu_3Cr_4O_{12}$	$SrCuO_2$: F	
Intercalation to layered structure				
FeOCl	VOCl	TiOCl	CrOCl	TiNCl←mono-amine [55]
Zr_2N_2S [89]	Hf_2N_2S [89]	$Ca_xHf_2N_2S$	α-HfNBr	Ti_2PTe_2 ← Ag, Cu, Zn [90]
$Bi_2PdO_4F_x$	$Bi_{1.67}Pb_{0.33}PtO_4F_x$	Pb_3O_4 ← F	$Zr_5(N_4O)F_{6-x}$	Ti_2N_2S
Ti_2N_2O	$Hf_5(N,O)_8F_{6-x}$	Zr_2N_2O	Graphite← KH	graphite← B
$CsLaTe_2O_5Cl$				
perovskite and its related structure				
antiperovskite structure		Mn_3AlC	Mn_3SnC	Mn_3AlN
Mn_2CrN	Mn_3ZnN [91]	$AlNi_3C$	$Mn_3ZnN_{1-x}C_x$	$Mn_3InN_{1-x}C_x$
$Mn_3Sb_{1-x}Sn_xN$	$Mn_3Ag_{1-x}Sn_xN$	Ca_3SiO	Ca_3SnO	Ca_2PbO
$SrAg_3P$	$SrIr_3P$	$SrAu_3P$	Mg_3CNi_3	Ca_4OSb_2
$RhNCr_3$				
double perovskite structure		Ca_3OsO_6	Ca_2MnOsO_6	Ca_2CoOsO_6
Ca_2ZnOsO_6	Sr_3OsO_6	Sr_2LiOsO_6 [92]	Sr_2MnOsO_6	Sr_2FeOsO_6 [93]
Sr_2CoOsO_6 [93]	Sr_2NiOsO_6	Sr_2YOsO_6	Sr_2PbOsO_6	Sr_2DyOsO_6
$Ba_2(Sr_2,Ca_2)FeOsO_6$	$Ba_2YScOsO_6$	Sr_4FeMoO_8		
normal perovskite		$SrGeO_3$ [94]	$(Ca_{1-x}Y_x)GeO_3$	$(Sr_{1-x}La_x)GeO_3$ [94]
$CaTiO_{3-x}H_x$	$SrTi(O,H)_3$ (thin film)	$EuTiO_{3-x}H_x$	$CaVO_3$:H	$SrVO_3$:H

Table 2. (Continued.)

	[95]			
$SrCrO_2H$ [96]	$Sr_{1-x}Ba_xCrO_2H$ (x = 0.1-0.4)	$LnCrO_3$ (Ln = La, Sm, Nd)	$BaTiO_{3-x}$	$BaZrO_3$:H
$SrSnO_{3-\delta}$	$SrNbO_2N$	$BaSnO_{3-\delta}$	$NaIrO_3$	$Na_{1-x}Ca_xIrO_3$
$SrMoO_{2.5}N_{0.5}$	$BaBiS_3$			
other perovskite		$A_2Ru_2O_5$	$LaBaMn_2O_6$	$YBaMn_2O_6$
$A_2Cr_2O_5$				
cuprate superconductor and its related structure				
$(Sr,Eu)CuO_2$	$(Sr,Pb)CuO_2$	Bi_2CuO_4 CaH_x	Bi_2CuO_4-CuF_2	BiOCuS
YBCO:H	$(Cu_2S_2)Sr_3Fe_2O_5$	$Sr_3FeNiCu_2Se_2O_5$	$Sr_3Ni_2Cu_2Se_2O_5$	$Sr_3Cu_4Se_2O_5$
$Bi_2YCu_2O_4Se_2$	$Bi_2SrCu_2O_4Se_2$	$SrLa_2Cu_4Se_2O_5$	$A_2CuO_x(OH)_y$	$LaSrTiO_4$
Sr_2CrO_4	Ca_2CrO_4	$Sr_3Cr_2O_7$	$Ca_3Cr_2O_7$	$A_4Cr_3O_{10}$ (A = Sr, Ca)
$Sr_{2-x}Na_xCrO_4$	$YCaCrO_4$	$Srn_{1-x}K_xMn_nO_{3n+1}$ (n = 1, ∞)		
clathrate structure				
$Ca_3Ni_{12}B_6$	$Sr_3Ni_{12}B_6$	KC_{24}	Li_xC_{60}	K_xC_{60}
Ca_xC_{60}	Ba_xC_{60}	Mg_2C_{60}	Ba_3C_{60} [97]	Ca_xAlN
Li_xSi_{136}	$Na_{32}Si_{136}$ [98]	K_xSi_{136}	Mg_xSi_{136}	Ca_xSi_{136}
Ba_xSi_{136}				
Pyrite structure				
FeS_{2-x}	$PtSb_2$	$(Pt,Pd)Sb_2$	$(Pt,Ir)Sb_2$ [99]	$Pt(Sb,As)_2$
$Pt(Sb,Te)_2$	$Pt(Sb,Sn)_2$	$(Pt,Au)Sb_2$	$IrSb_2$	
other materials				
carbide		CaC_2	BaC_2	YC_2
nitride		Ti_3N_4	Zr_3N_4	Hf_3N_4
VCrN	Mg_xAlN	MnN (thin film)	CoN (thin film)	
oxide		TiO_x (anatase) [100]	Cr_3O	Cr_nO_{2n-1} (n = 3, 4)
MnO_2 (nanosheet)	Co_3O_4: H	NiO: H	GeO_2 (HP phase)	h-WO_3: H
$BaScO_2H$	$Ti_3O_{4.9}N_{0.1}$	$Ti_4O_{6.99}N_{0.01}$	$(Ir,Ru)O_2$	$CuAl(O,N)_2$
$LaSiO_3H$	$NaTi_2O_4$	$Bi_4Ti_3O_{12}$: H	$Sc_4Ti_3O_{12}$	$Cs_{0.7}Ti_{1.825}O_4$: F
$La_2Ti_2O_{7-x}$	Ba-Ti-O glass + e	$Y_2Ti_2O_{7-x}$	$Sr_2TiO_3F_2$	$Cr_{1-x}Ti_xO_2$
$Cr_{1-x}V_xO_2$	nSrO · V_2O_3 (n= 4, 2, 1)	$Bi_xV_8O_{16}$	CaV_2O_5	LiV_2O_4
$LaVO_3$: H	$LaVO_4$: H	$NaCr_2O_4$ [101]	$Ca_{1-x}Na_xCr_2O_4$	$CaCr_2O_4$
$BaCr_2O_4$	$SrCu_3Cr_4O_{12}$	$BaCu_3Cr_4O_{12}$	$YCu_3Cr_4O_{12}$	$LaCu_3Cr_4O_{12}$
$CeCu_3Cr_4O_{12}$	$LuCu_3Cr_4O_{12}$	$EuCu_3Cr_4O_{12}$	$BiCu_3Cr_4O_{12}$	$Cr_{1-x}Mn_xO_2$
Ag_2MnO_3	Pb_2MnO_4: F	$LiMn_2O_4$	$Sr_3Co_2O_6$ [102]	$Ba_3Co_2O_6(CO_3)_x$
$Sr_{3-x}Y_xCo_2O_6$ [103]	$Sr_{3-x}Ca_xCo_2O_6$	$Sr_3Co_{2-x}Zn_xO_6$	$Sr_3Co_{2-x}Fe_xO_6$	Y-ZrO_{2-x}
$SrNb_2O_6$: F	$Ba_5Nb_4O_{15-x}$	$Ba_2Nb_3O_9$: F	$PbMoO_4$: N	$Ca_2Nb_2O_{6-x}F_{1+x}$
Sr_2NbO_3N	$Li_2Ir_{1-x}Ru_xO_3$ [104]	$La_4Ru_2O_{10}$	$Bi_3Ru_3O_{11}$	$Sr_3Ru_2O_7Cl_2$
$Sr_3Ru_2O_7F_2$	$LaCu_3Ru_4O_{12}$	$CdRh_2O_4$ [105]	$Cd_{1-x}Na_xRh_2O_4$	$La_2Pd_2O_5$
$BaSbO_3$	CsW_2O_6	$SrWO_2N$	$LiOsO_3$ [106]	$Na_{1-x}Ca_xOsO_3$
$KOsO_3$	Ca_2LiOsO_6 [107]	$Ca_2Os_2O_7$	$Ca_5Os_2O_{12}$	Ba_2OsO_5
Bi_2OsO_6	$Pb_2Os_2O_7$	$Pb_2Ir_2O_7$	Ag_2BiO_3	$Ba_{1-x}K_xBiO_3$ (junction)
chalcogenide		Cu_xS	$Cu(S,As)$	KMo_3S_3
$SrPt_3S$	$BaPt_3S$	InV_6Se_8	$Pt_xBi_2Se_3$	KMo_3Se_3
$Cu_xBi_2Se_3$	$Cu_xBi_2Te_3$	$Pd_xBi_2Te_3$	Li_xZrTe_3	SnTe
pnictide		CoP	NiP	(Co,Ni)P
$La_xIr_4P_{12}$	Mg_xAlP	$BaNi_2P_4$	$BaPd_2P_4$	$(Y_{1-x}Eu_x)P$
$SrPt_3Sb$	$BaPt_3Sb$	La_3TiSb_5	La_3VSb_5	La_3CrSb_5
La_3MnSb_5	La_3TiBi_5	La_3VBi_5	La_3CrBi_5	La_3ZtBi_5
La_3HfBi_5				
silicide, germanide, stannide, plumbide		(Ca, Mg)Si_2	$Fe_3Al_2Si_4$	$MgAl_2Si_2$
Mg_4AlSi_6	$Mg_{1.3}Ga_{0.7}Si$	Li_xPtSi_3	$BaMg_2Si_2$	$Ti_2Ru_3Si_4$
BaPdSi	SrPdSi	$BaMg_2Ge_2$	Rh_3Ge_7	$BaMg_2Sn_2$
$BaMg_2Pb_2$				
halide		$K_{1+x}TiF_4$	$K_{1-x}TiF_4$	$Zr_5(N_4Na)F_6$
$Zr_5(N_4H$-$)F_6$	$CsSnI_3$	La_2TeI_2		
metal		$ZrMn_2$	Zr_3Pb_4	