2010 Spring

“Amorphous Materials”

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Glass formation

Retention of liquid phase

Formation of crystalline phases

Thermodynamical point
Small change in free E. (liq.→ cryst.)

Kinetic point
Low nucleation and growth rates

Structural point
Highly packed random structure

Empirical rules

(1) multi-component alloy system (2) significant difference in atomic size ratios
(3) negative heats of mixing (4) close to a eutectic composition
(5) compositions far from a Laves phase region

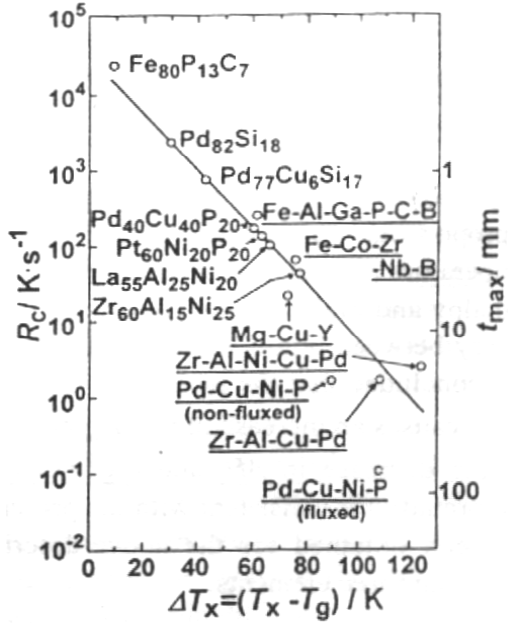
- ***Higher*** **degree of dense random packed structure**
- ***Suppression*** **of nucleation and growth of crystalline phase**

→ ***High glass-forming ability (GFA)***

GFA Parameters on the basis of thermodynamic or kinetic aspects :

1) ΔT_x parameter = T_x - T_g

- quantitative measure of glass stability toward crystallization upon reheating the glass above T_g: stability of glass state
- cannot be considered as a direct measure for GFA



2) K parameter = $(T_x-T_g)/(T_l-T_x) = \Delta T_x/(T_l-T_x)$

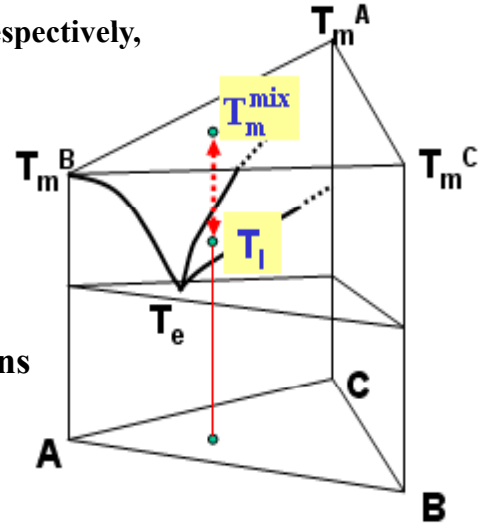
- based on thermal stability of glass on subsequent reheating
- includes the effect of T_l , but similar tendency to ΔT_x

3) ΔT^* parameter = $(T_m^{mix} - T_l)/ T_m^{mix}$

- $$T_m^{mix} = \sum_i^n n_i \cdot T_m^i$$

(where n_i and T_m^i are the mole fraction and melting point, respectively, of the i th component of an n-component alloy.)

- evaluation of the stability of the liquid at equilibrium state
- alloy system with deep eutectic condition ~ good GFA
- for multi-component BMG systems: insufficient correlation with GFA

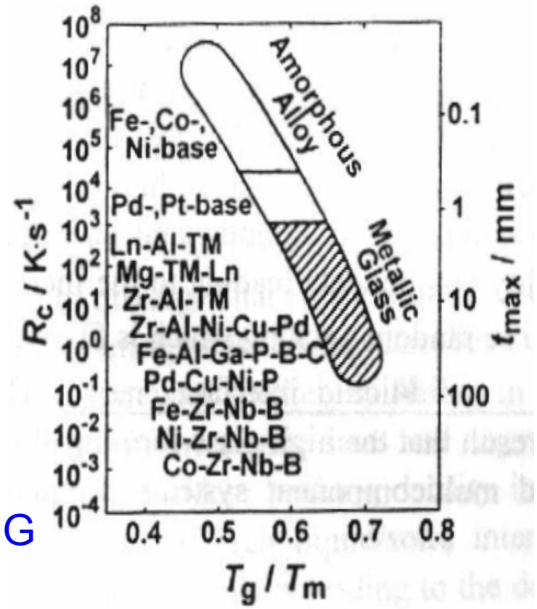


➡ T_m^{mix} represents the fractional departure of T_m with variation of compositions and systems from the simple rule of mixtures melting temperature

GFA Parameters on the basis of thermodynamic or kinetic aspects :

4) T_{rg} parameter = T_g/T_l

- kinetic approach to avoid crystallization before glass formation
- Viscosity at T_g being constant, the higher the ratio T_g/T_l, the higher will be the viscosity at the nose of the CCT curves, and hence the smaller R_c
- T_l ↓and T_g ↑ ► lower nucleation and growth rate ► GFA ↑

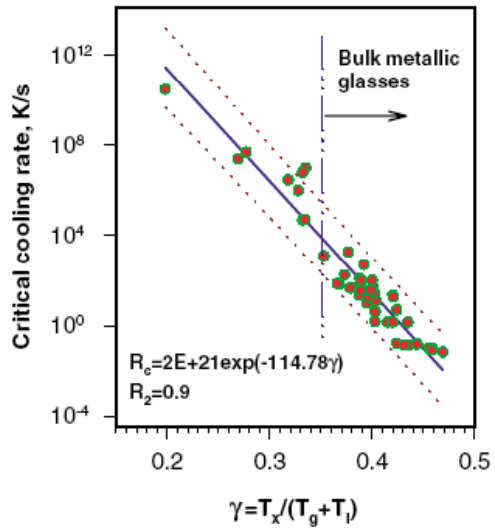


- significant difference between T_l and T_g in multi-component BMG
- insufficient information on temperature-viscosity relationship

► insufficient correlation with GFA

5) γ parameter = T_x / (T_l + T_g)

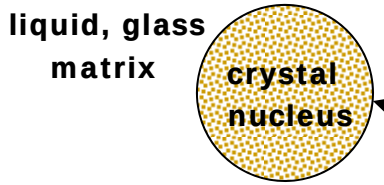
- thermodynamic and kinetic view points - relatively reliable parameter
- stability of equilibrium and metastable liquids: T_l and T_g
- resistance to crystallization: T_x



Glass formation: destabilizing the crystalline phase

- **Crystal nucleation rate (*J*)**

- Assuming a spherical shape of the nucleus and a homogeneous manner of the nucleation process



interfacial energy

$$J = \frac{10^{36}}{\eta(T)} \exp\left[-\frac{16\pi}{3kT} \frac{\sigma^3}{(\Delta G_v(T))^2} f(\theta) \right] m^{-3} s^{-1}$$

nucleation events per volume, time

Viscosity

Gibbs free energy difference per volume

(a) first-order approximation (i.e., $\Delta G = \Delta S_m (T_m - T)$; ΔS_m is the entropy of fusion per volume)

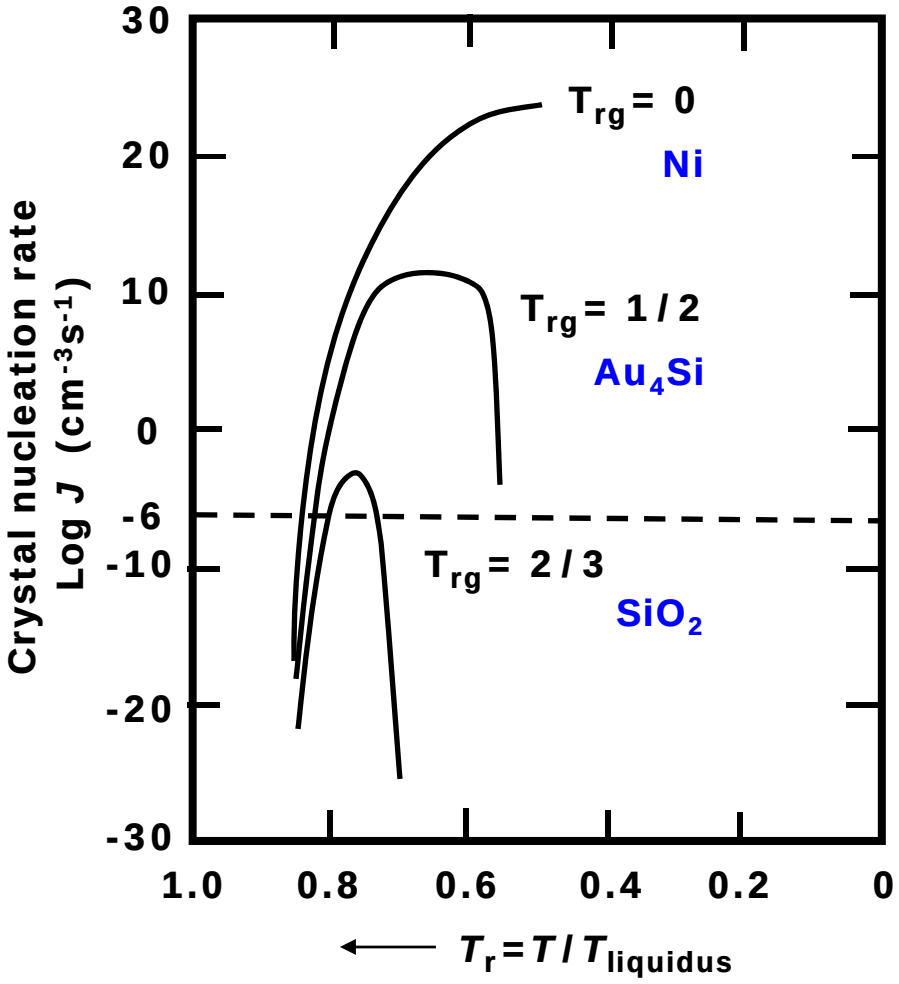
(b) simplified Vogel-Fulcher-Tamman (VFT) equation $\eta = 10^{-3.3} \exp\left(\frac{3.34}{T_r - T_{rg}}\right)$

(c) $T_r = T/T_m$ and $\Delta T_r = (T_m - T)/T_m = 1 - T_r$

Criterion for glass formation

T_{rg} parameter $= T_g / T_m$

: ability to avoid crystallization during cooling



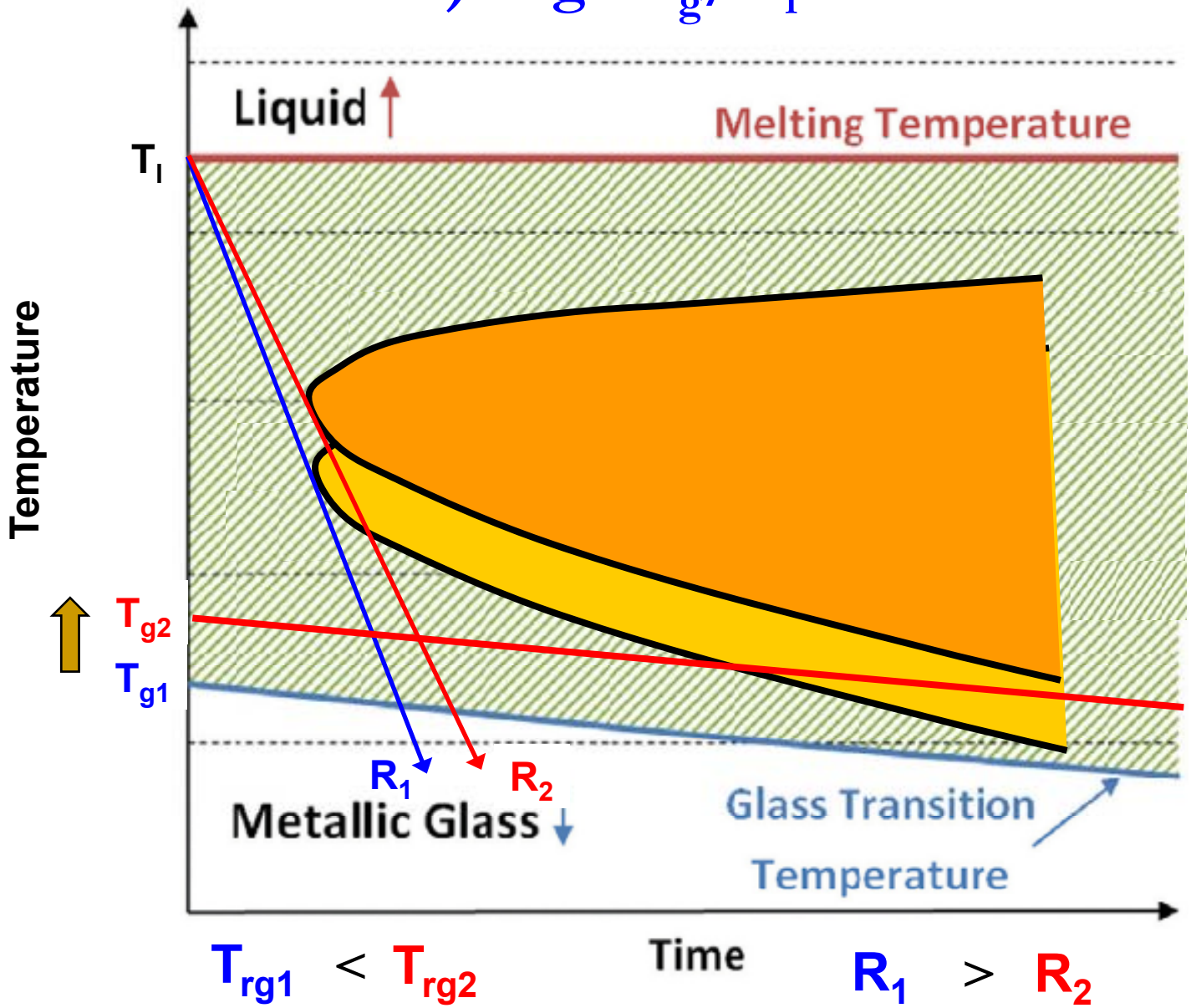
$T_{rgNi} < T_{rgAu4Si} < T_{rgSiO2}$

$R_{Ni} > R_{Au4Si} > R_{SiO2}$

Turnbull, 1959 ff.

Time Temperature Transformation diagram:

4) Trg= T_g / T_l



$T_{rg1} < T_{rg2}$ $R_1 > R_2$

Time Temperature Transformation diagram:

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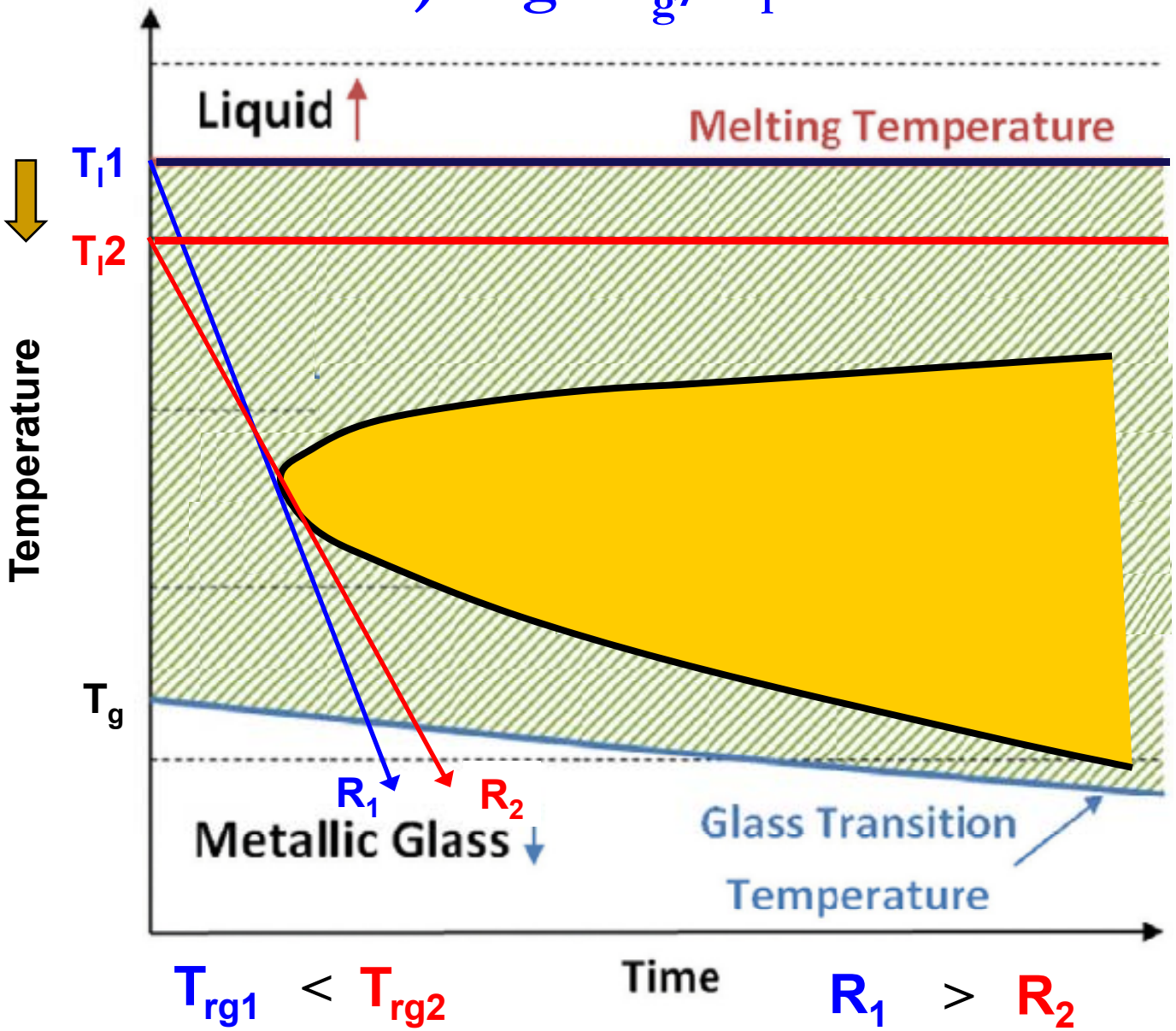

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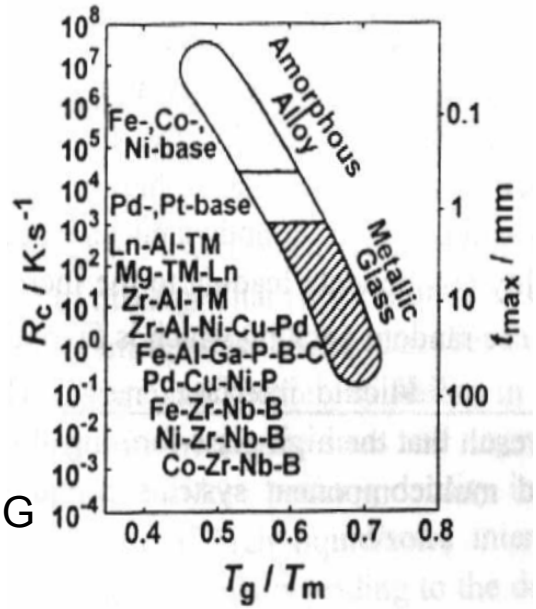
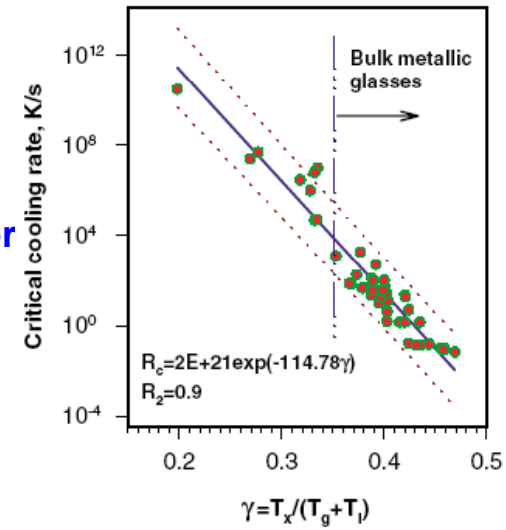
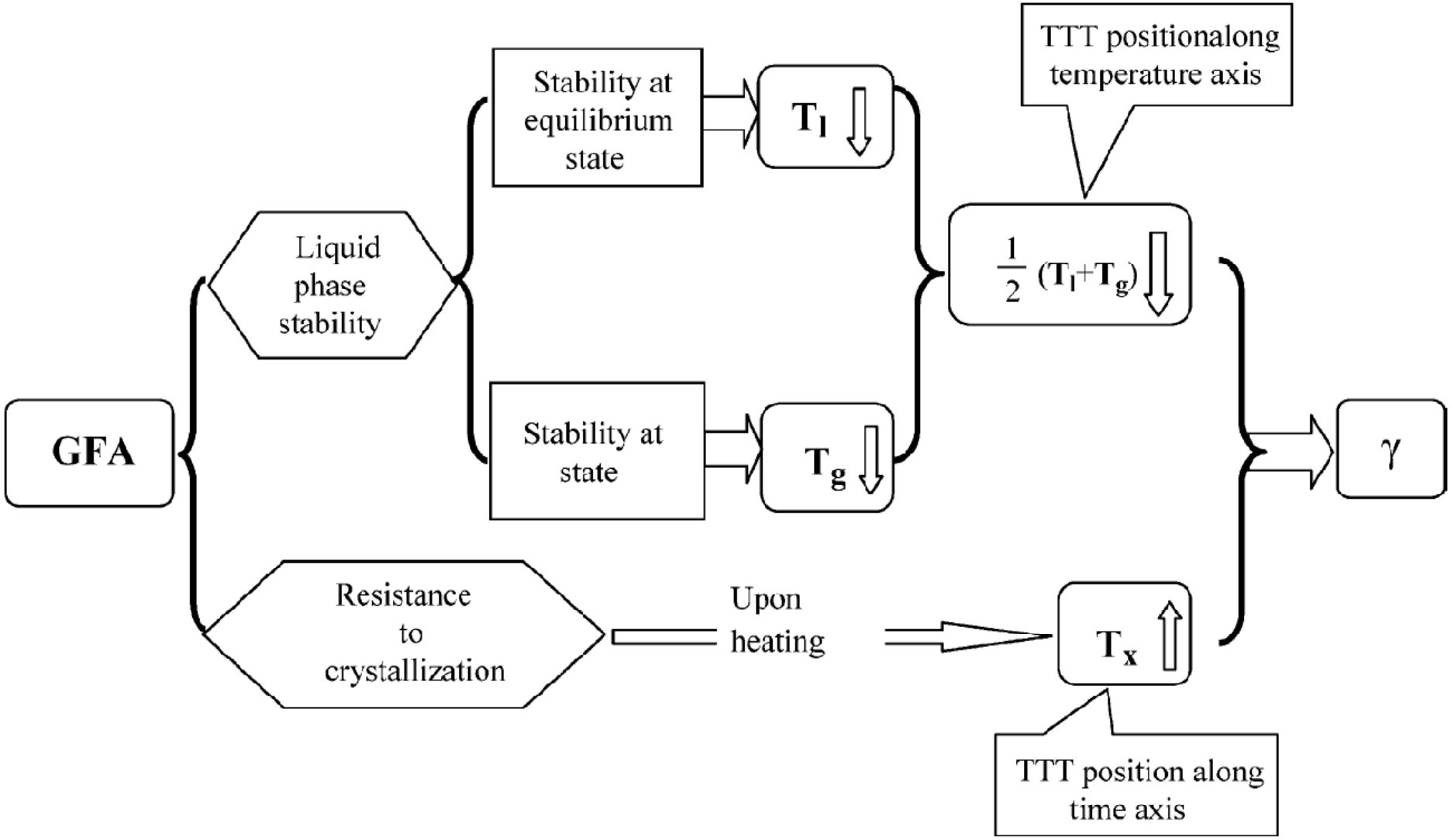


- significant difference between T_l and T_g in multi-component BMG
- insufficient information on temperature-viscosity relationship
- ► insufficient correlation with GFA

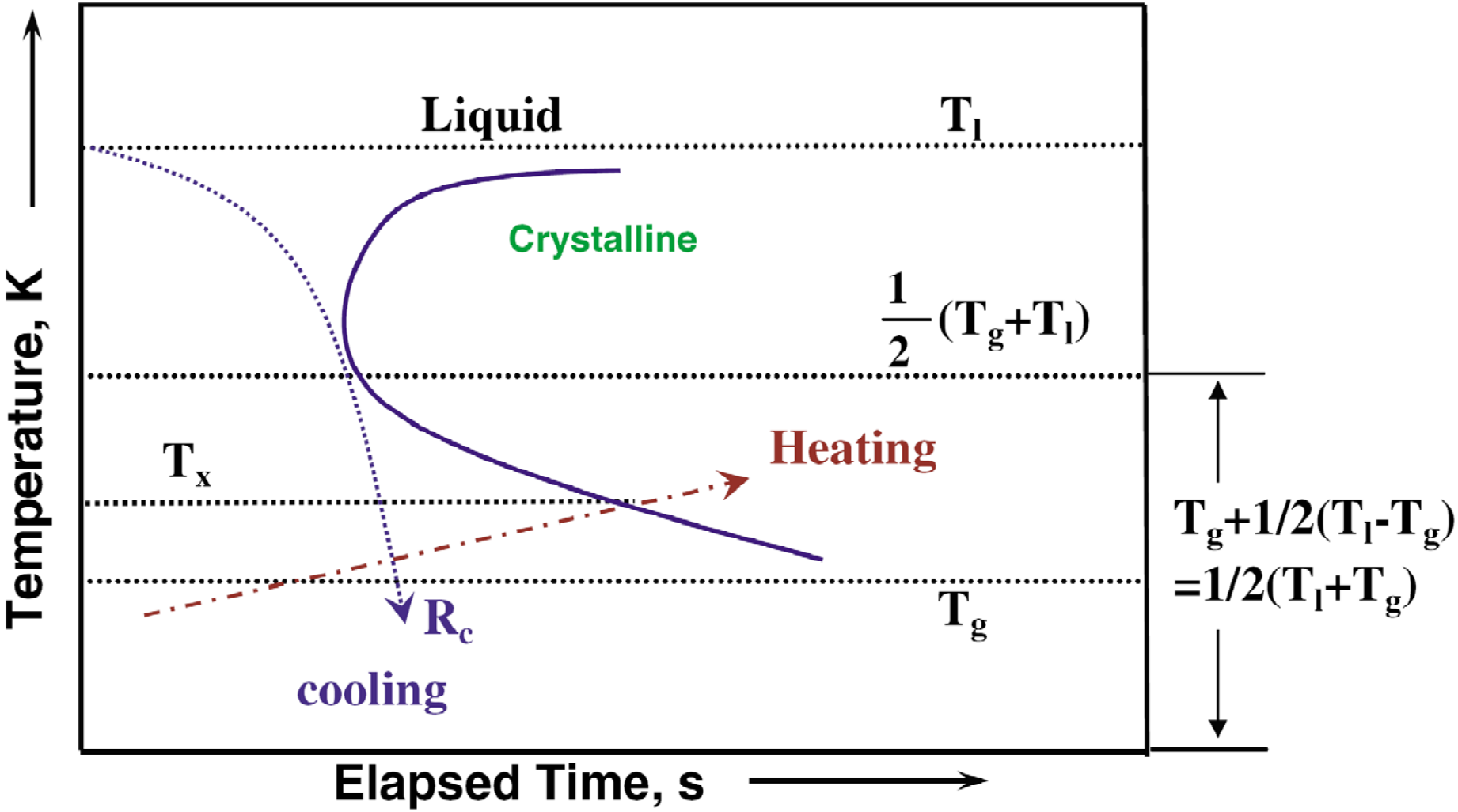
5) γ parameter = T_x / (T_l + T_g)

- thermodynamic and kinetic view points - **relatively reliable parameter**
- stability of equilibrium and metastable liquids: T_l and T_g
- resistance to crystallization: T_x




GFA
Liquid phase stability
Resistance to crystallization
Stability at equilibrium state
Stability at state
T_l
T_g
$\frac{1}{2}(T_l+T_g)$
TTT positionalong temperature axis
Upon heating
T_x
TTT position along time axis
γ

$$\gamma \propto T_x\left[\frac{1}{2(T_g + T_l)}\right] \propto \frac{T_x}{T_g + T_l}$$



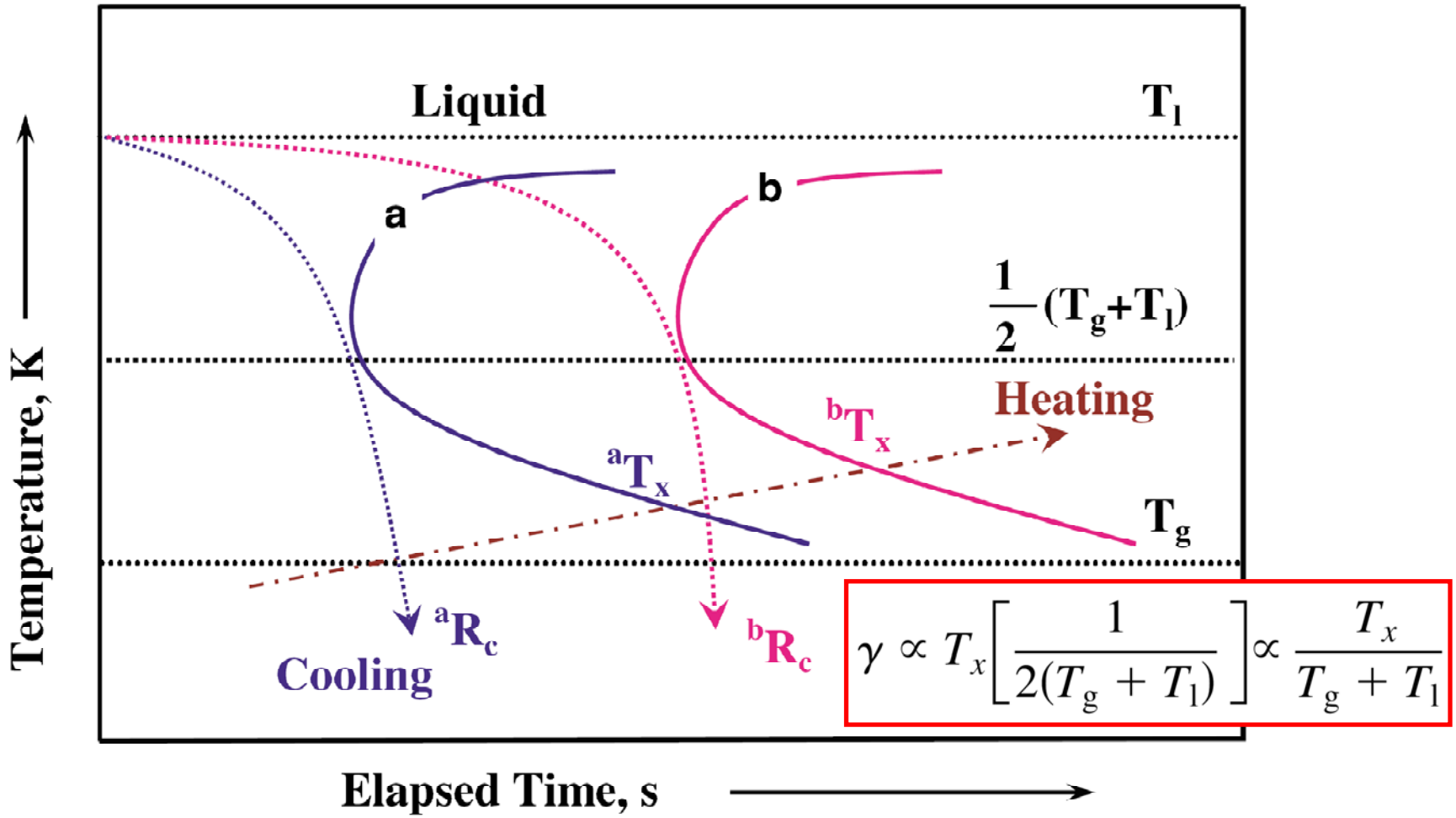


FIG. 2 (color online). Schematic TTT curves showing the effect of T_x measured upon continuous heating for different liquids with similar T_l and T_g; liquid b with higher onset crystallization temperature ^bT_x ($^aT_x < {}^bT_x$) shows a lower critical cooling rate ^bR_c ($^bR_c < {}^aR_c$).

GFA Parameters *on the basis of thermodynamic or kinetic aspects*

GFA parameters	Expression	Year established	
T_{rg}	T_g / T_l	1969	D.Turnbull,Contemp.Phys.10(1969) 473
K	$(T_x-T_g) / (T_l-T_x)$	1972	A.Hruby, Czech. J.Phys. B 22 (1972) 1187
ΔT^*	$(T_m^{mix}-T_l) / T_m^{mix}$	1978	I.W.Donald, J.Non-Cryst.Solids 30 (1978) 77
ΔT_x	$T_x - T_g$	1993	A.Inoue, J.Non-Cryst.Solids 156-158(1993)473
γ	$T_x / (T_l+T_g)$	2002	Z.P.Lu, C.T.Liu, Acta Mater. 50 (2002) 3501
δ	$T_x / (T_l-T_g)$	2005	Q.J.Chen,Chiness Phys.Lett.22 (2005) 1736
α	T_x / T_l	2005	K.Mondal, J.Non-Cryst.Solids 351(2005) 1366
β	$T_x / T_g + T_g / T_l$	2005	K.Mondal, J.Non-Cryst.Solids 351(2005) 1366
φ	$(T_g / T_l)(T_x-T_g / T_g)^a$	2007	G.J.Fan,J.Non-Cryst. Solids 353 (2007) 102
γ_m	$(2T_x - T_g) / T_l$	2007	X.H.Du,J.Appl.phys.101 (2007) 086108
β	$(T_g / T_l- T_g)(T_g / T_l- T_g)$	2008	Z.Z.Yuan, J. Alloys Compd.459 (2008)
ξ	$\Delta T_x / T_x + T_g / T_l$	2008	X.H.Du,Chinese Phys.B 17(2008) 249

No universal model **to predict and evaluate what families of alloy compositions are likely to form BMGs**

Combination of categories

that are viewed as decisive in the formation of amorphous alloys

New criterion

for predicting and evaluating Glass Forming Ability

- **useful guideline for BMG alloy system design**

- save time and experimental cost

→ **new alloy system with enhanced GFA**

Approach 1. combine thermodynamic and structural points

$$\sigma = \Delta T^* \times P'$$

ΔT^* : **Relative decrease of melting temp.** P' : **Effective atomic mismatch per solute atom**

$$\Delta T^* = \frac{T_m^{mix} - T_l}{T_m^{mix}}$$

$$P' = \frac{C_B}{C_B + C_C}\left|\frac{v_B - v_A}{v_A}\right| + \frac{C_C}{C_B + C_C}\left|\frac{v_C - v_A}{v_A}\right|$$

(where, $T_m^{mix} = \sum x_i T_m^i$, x_i = molefraction, T_m^i = melting point)

(where, C_i(i=A,B,C) = solute content, v_i = atomic volume)

Approach 2. combine thermodynamic and kinetic points

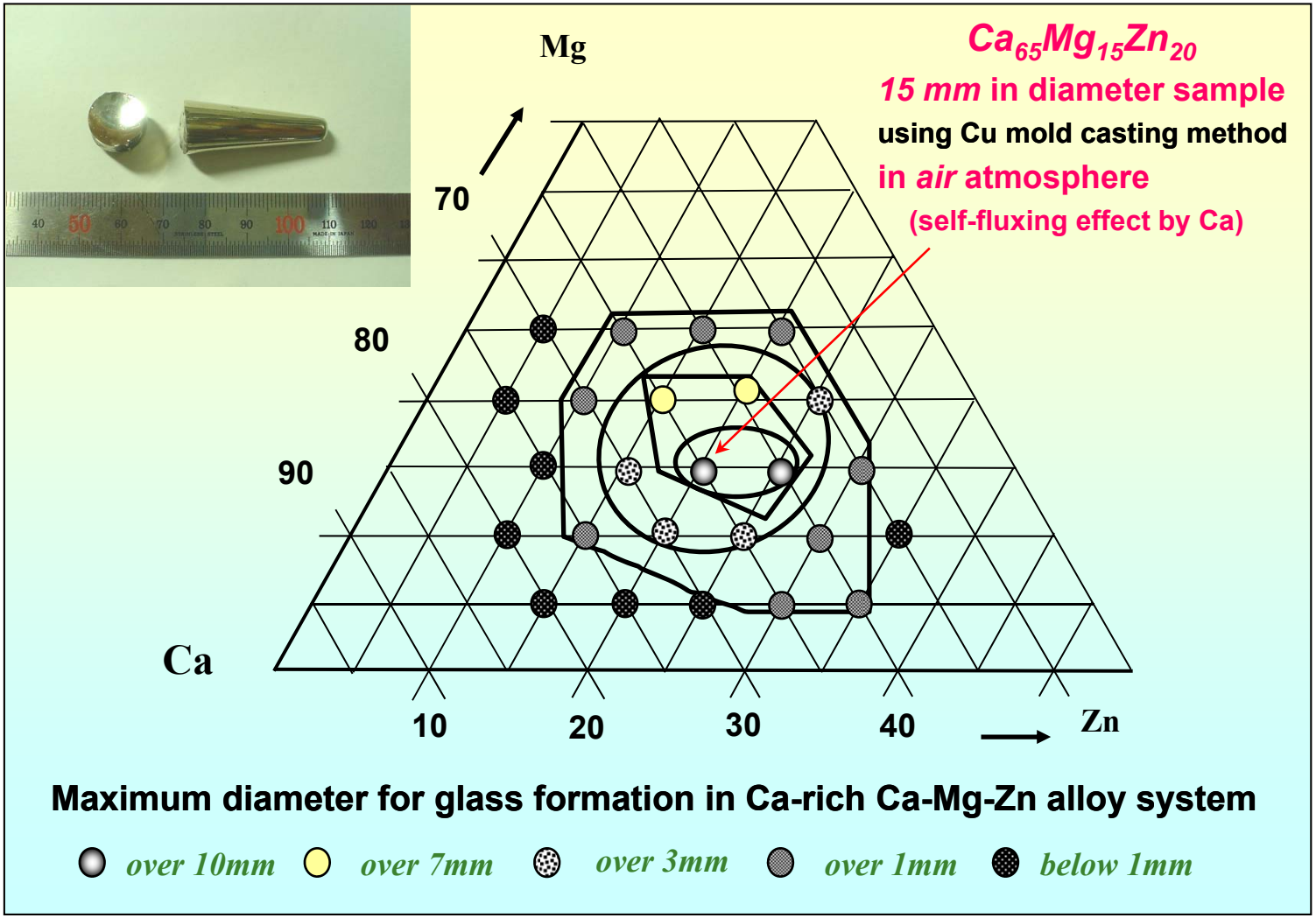
$$\varepsilon = \frac{\Delta T_m + \Delta T_x + T_x}{T_m^{mix}}$$

$\Delta Tm + \Delta Tx$: ***Liquid phase stability*** + ***Tx*** : ***Resistance to cristallization***

(where, ΔTm = Tmmix – Tl , ΔTx = Tx – Tg)

(where, Tx = crystallization onset temperature)

Ca-Mg-Zn alloy system



* J. Mater. Res. 19, 685 (2004)
* Mater. Sci. Forum 475-479, 3415 (2005)

Thermodynamic aspect for glass formation

Relative decrease of melting temperature

$$\Delta T^* = \frac{T_m^{mix} - T_l}{T_m^{mix}}$$

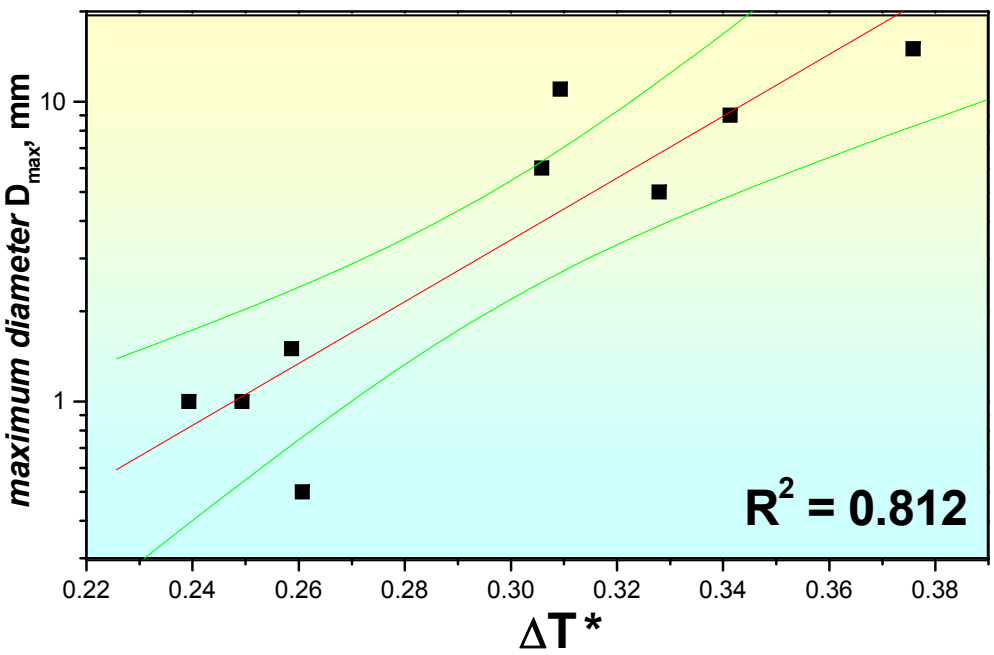
: ratio of Temperature difference between liquidus temp. T_l and imaginary melting temp. T_m^{mix} to T_m^{mix}

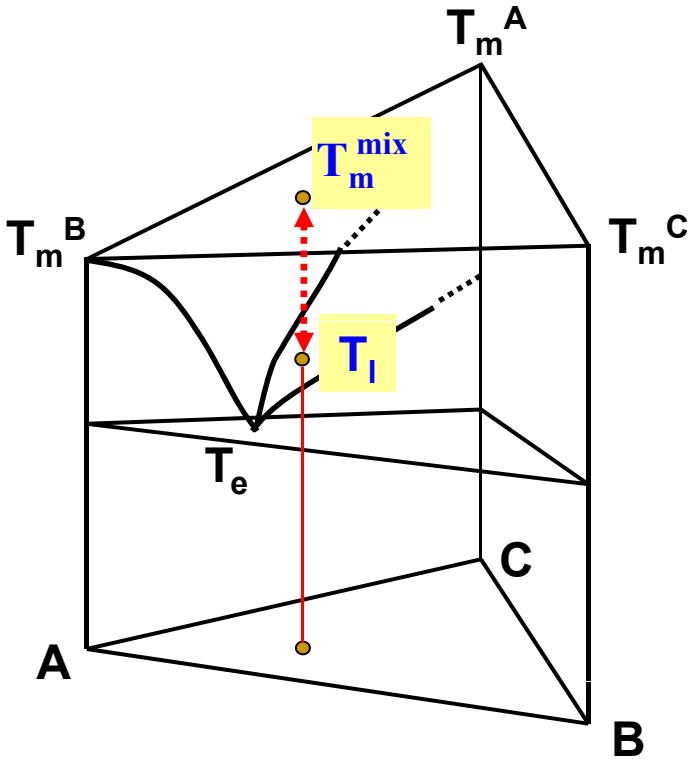
(where, $T_m^{mix} = \sum x_i T_m^i$, x_i = molefraction, T_m^i = melting point)

by I.W. Donald et al. (*J. Non-Cryst. Solids*, 30, 77 (1978))

➡ $\Delta T^* \geq 0.2$ in most of glass forming alloys

Ca-Mg-Zn alloy system



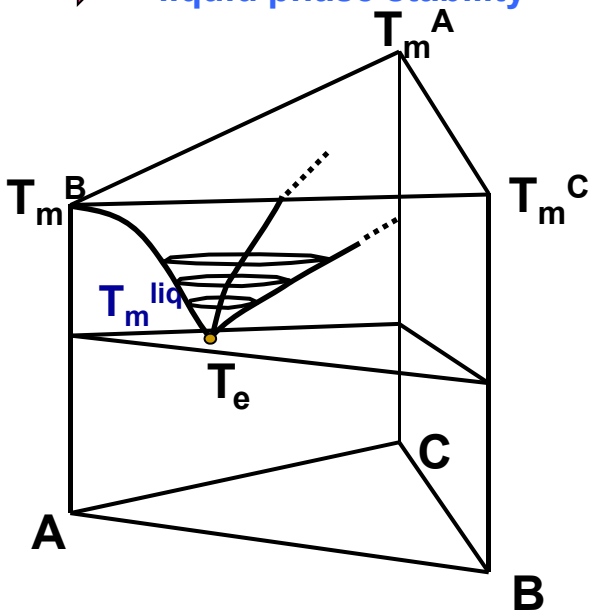


IH3 = R^2 : regression coefficient

σ parameter (thermodynamic and atomic configuration aspects)

ΔT^* : Relative decrease of melting temp.

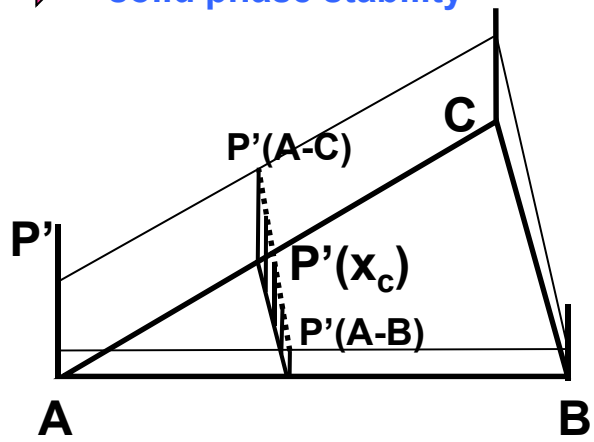
➡ liquid phase stability



Deep eutectic condition

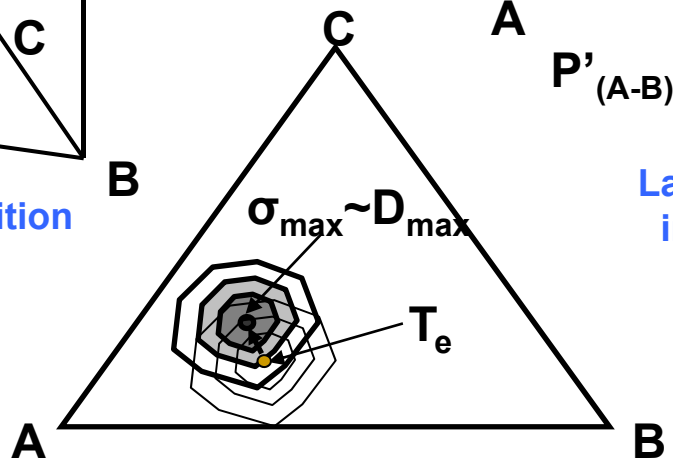
P' : Effective atomic mismatch per solute atom

➡ solid phase stability



$P'_{(A-B)} \leq P'(Xc) \leq P'_{(A-C)}$

Large difference in atomic size



New criterion for GFA, σ parameter $\sigma = \Delta T^* \times P'$

* Appl. Phys. Lett., 86, 061907 (2005)

Structural aspect for glass formation

- **Effect of atomic size difference can be represented as follows;**

$$P = C_B \left| \frac{v_B - v_A}{v_A} \right| + C_C \left| \frac{v_C - v_A}{v_A} \right|$$

$$P' = \frac{C_B}{C_B + C_C} \left| \frac{v_B - v_A}{v_A} \right| + \frac{C_C}{C_B + C_C} \left| \frac{v_C - v_A}{v_A} \right|$$

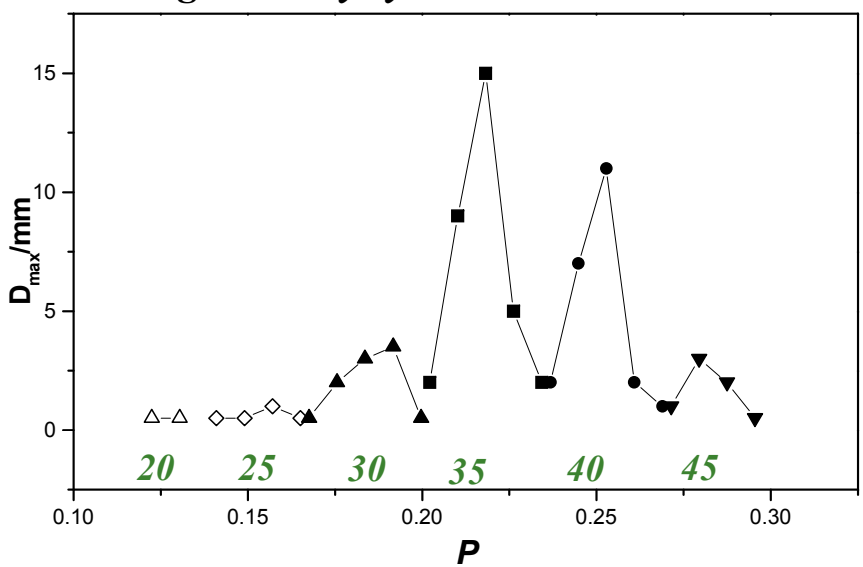
Where, C_i(i=A,B,C) = solute, v_i = content atomic volume

; effective atomic mismatch of solute atom

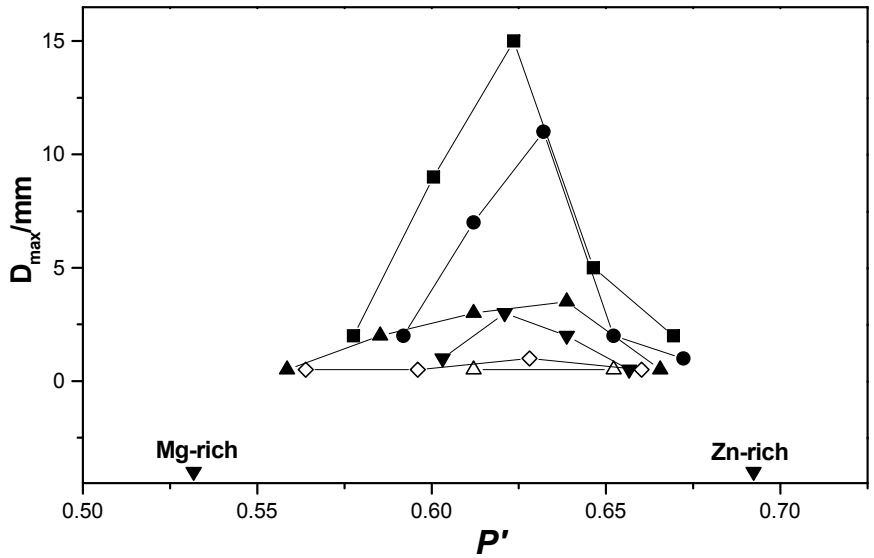
by dividing by the total amount of solute contents

*** Metall.& Mater. Trans. A 32, 200 (2001)**

Ca-Mg-Zn alloy system



Similar trend of D_{max} with P

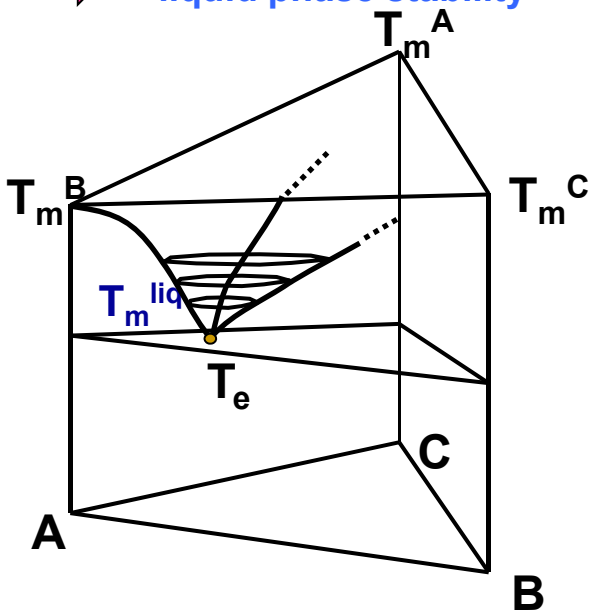


Maximum dia.(D_{max}) at P'=0.625

σ parameter (thermodynamic and atomic configuration aspects)

ΔT^* : Relative decrease of melting temp.

➡ liquid phase stability



Deep eutectic condition

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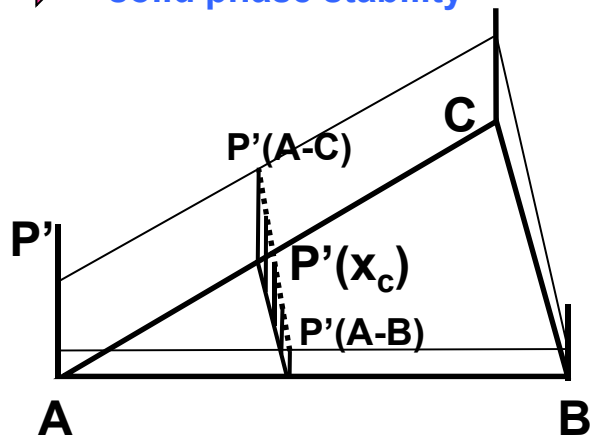
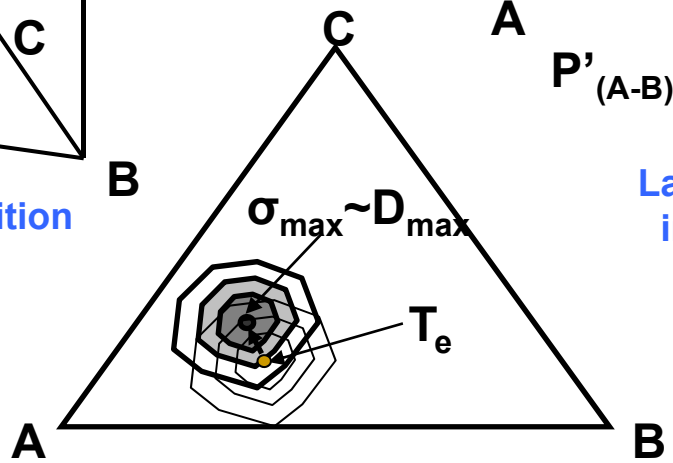
➡ solid phase stability



$P'_{(A-B)} \leq P'(Xc) \leq P'_{(A-C)}$

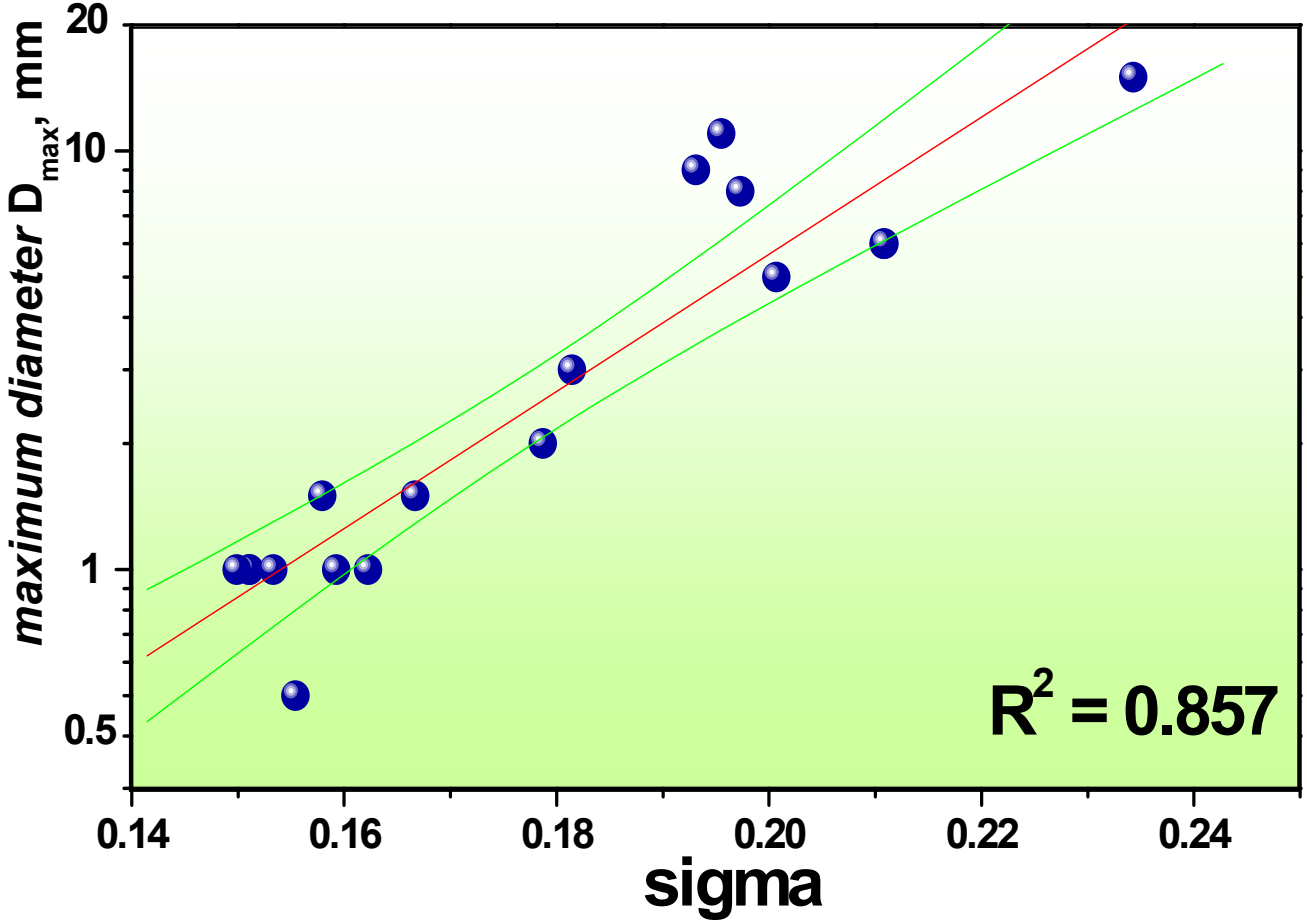
Large difference in atomic size



New criterion for GFA, σ parameter $\sigma = \Delta T^* \times P'$

* Appl. Phys. Lett., 86, 061907 (2005)

1) Calculation of GFA parameters in Ca-Mg-Zn alloy system



*** Sigma, σ parameter has a stronger correlation with GFA than other parameters suggested so far (ΔT_x: R^2=0.358, T_{rg}: R^2=0.787, K : R^2=0.607) in Ca-Mg-Zn alloy system.**

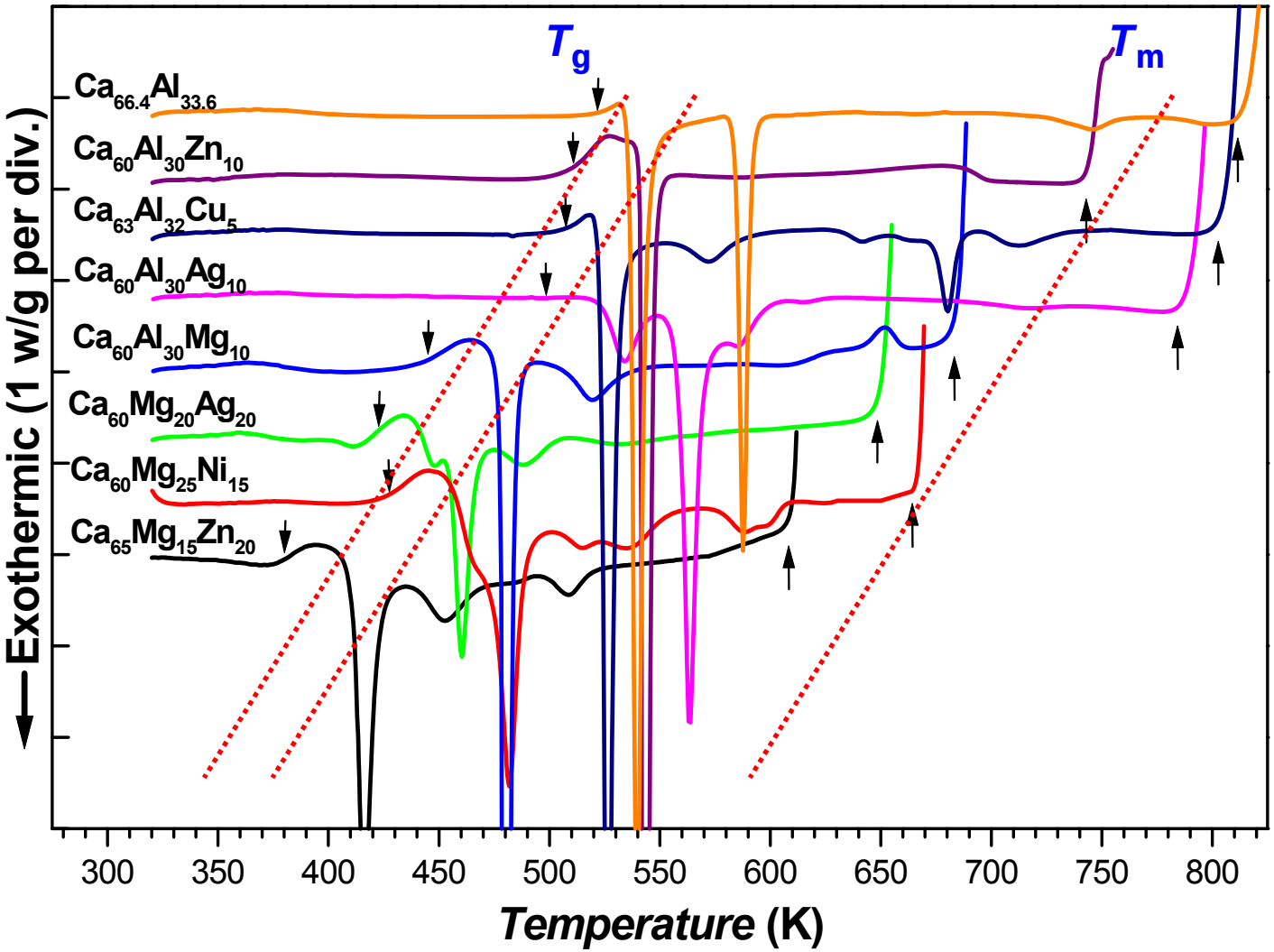
* J. Metastable and Nanocrystalline Materials, 24-25, 697 (2005)

2) Application of σ parameter for BMG-forming Ca-based ternary systems

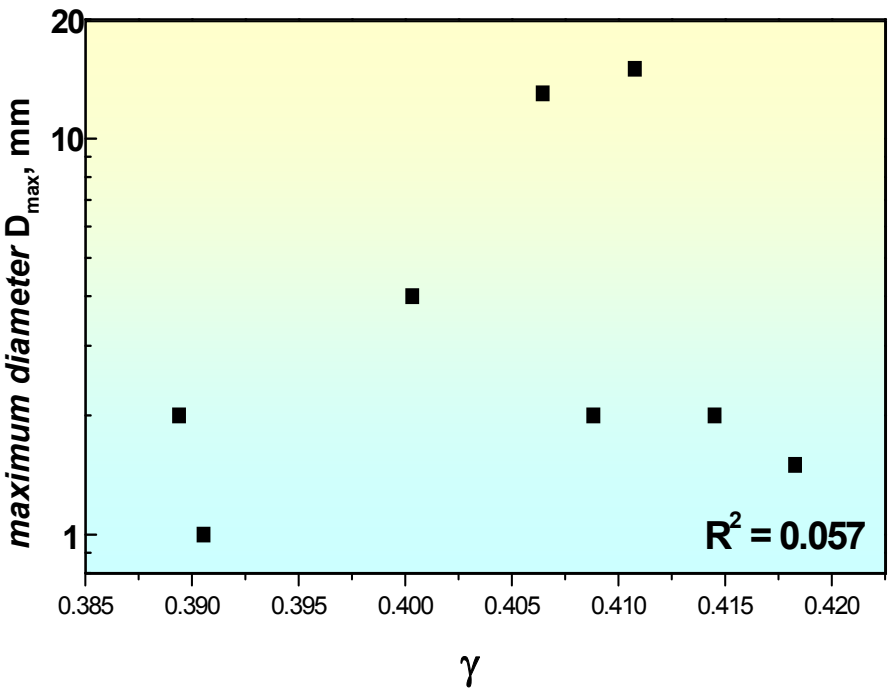
Thermal analysis, GFA parameters and maximum diameter (D_{max}) for glass formation in the Ca-based ternary BMG systems

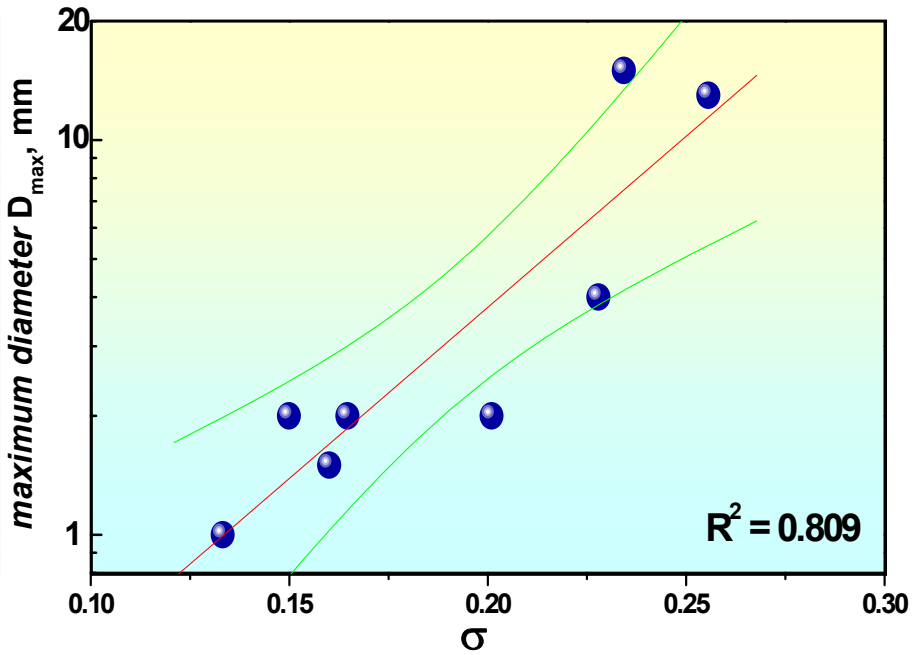
	T_g	T_x	T_l	T_l-T_g	ΔT_x	T_{rg}	K	γ	ΔT*	σ	D_{max}
$Ca_{65}Mg_{15}Zn_{20}$	379	412	624	245	33	0.607	0.156	0.411	0.376	0.234	15
$Ca_{60}Mg_{25}Ni_{15}$	431	453	683	252	22	0.631	0.095	0.406	0.409	0.256	13
$Ca_{65}Mg_{20}Ag_{20}$	422	440	677	255	18	0.624	0.075	0.400	0.384	0.228	4
$Ca_{60}Al_{30}Mg_{10}$	449	474	709	260	24	0.634	0.103	0.409	0.318	0.201	2
$Ca_{60}Al_{30}Ag_{10}$	483	534	805	322	51	0.600	0.187	0.415	0.248	0.165	2
$Ca_{63}Al_{32}Cu_{5}$	512	523	831	320	11	0.615	0.037	0.389	0.221	0.150	2
$Ca_{60}Al_{30}Zn_{10}$	517	540	775	258	24	0.667	0.100	0.418	0.238	0.160	1.5
$Ca_{66.4}Al_{33.6}$	527	534	841	315	8	0.626	0.025	0.391	0.200	0.133	1

DSC traces for BMG-forming Ca-based ternary systems



2) Calculation of GFA parameters in Ca-based BMG alloy systems





Sigma, σ parameter has a stronger correlation with GFA than other parameters suggested so far (ΔT_x: R^2=0.056, T_{rg}: R^2=0.080, K : R^2=0.148) in Ca-based BMG alloy systems.

* Appl. Phys. Lett. 86, 201912 (2005)

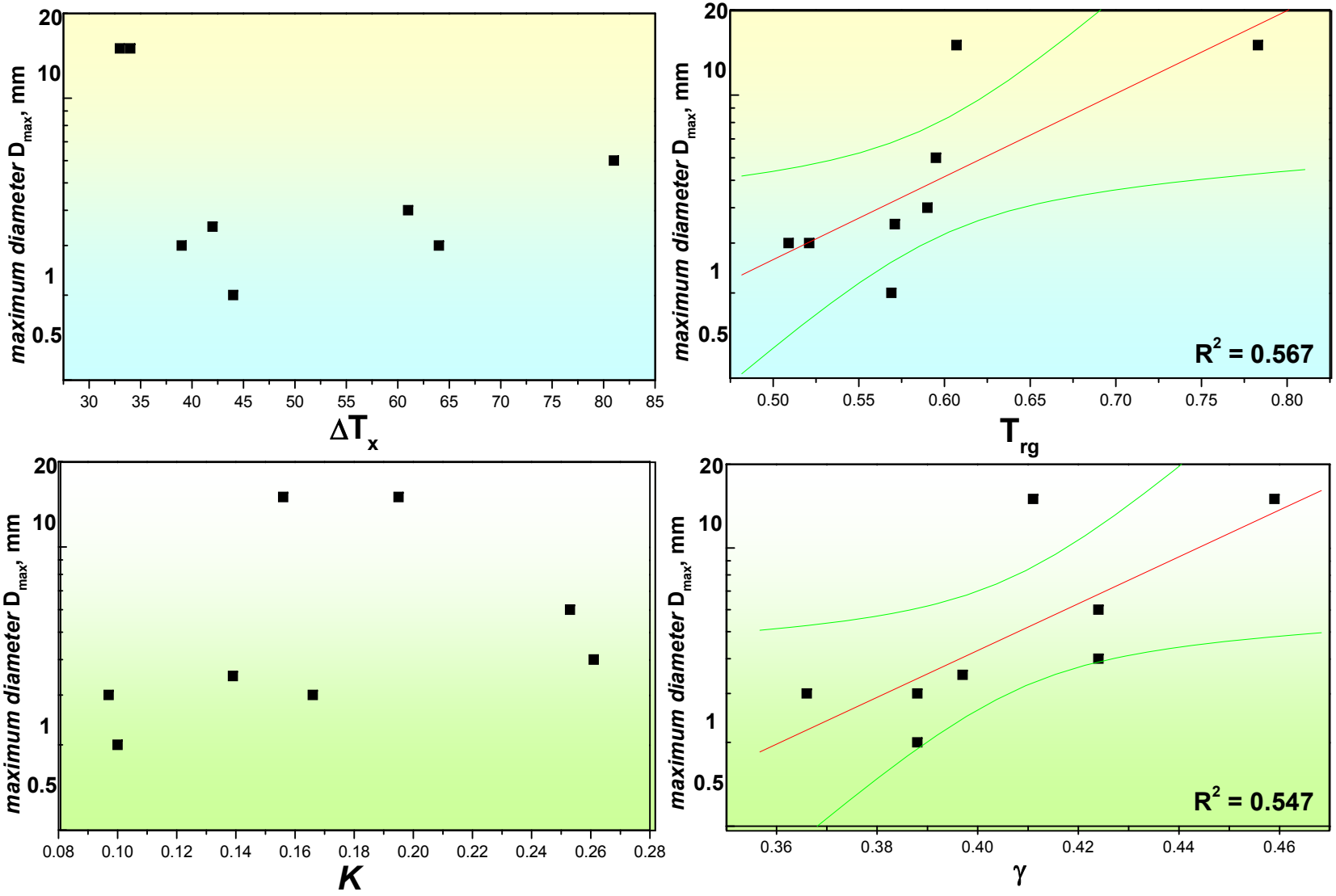
3) Application of σ parameter for BMG-forming ternary systems

Thermal analysis, GFA parameters and maximum diameter (D_{max}) for glass formation in the ternary BMG systems

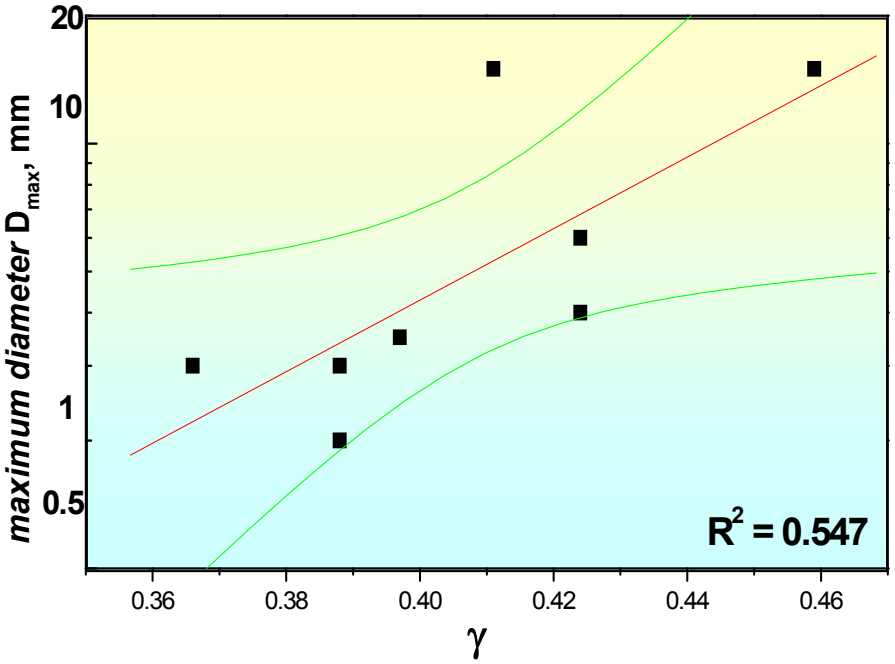
	T_g	T_x	T_l	T_m^{mix}	ΔT_x	T_{rg}	K	γ	ΔT*	P'	σ	D_{max}
$Ca_{65}Mg_{15}Zn_{20}$	379	412	624	1032	33	0.607	0.156	0.411	0.395	0.624	0.234	15
$Nd_{60}Fe_{30}Al_{10}$	750	784	958	1385	34	0.783	0.195	0.459	0.308	0.620	0.199	15
$Pd_{40}Ni_{40}P_{20}$	590	671	991	1519	81	0.595	0.253	0.424	0.348	0.476	0.158	6
$Mg_{65}Cu_{25}Y_{10}$	425	486	720	1062	61	0.590	0.261	0.424	0.322	0.470	0.167	4
$Mg_{65}Ni_{20}Nd_{15}$	459	501	805	1076	42	0.571	0.139	0.397	0.252	0.504	0.148	3.5
$La_{55}Al_{25}Ni_{20}$	491	555	941	1226	64	0.521	0.166	0.388	0.232	0.623	0.148	3
$La_{55}Al_{25}Cu_{20}$	456	495	896	1166	39	0.509	0.097	0.366	0.231	0.613	0.139	3
$Pd_{73.5}Cu_{10}Si_{16.5}$	642	686	1128	1785	44	0.569	0.100	0.388	0.368	0.300	0.107	2

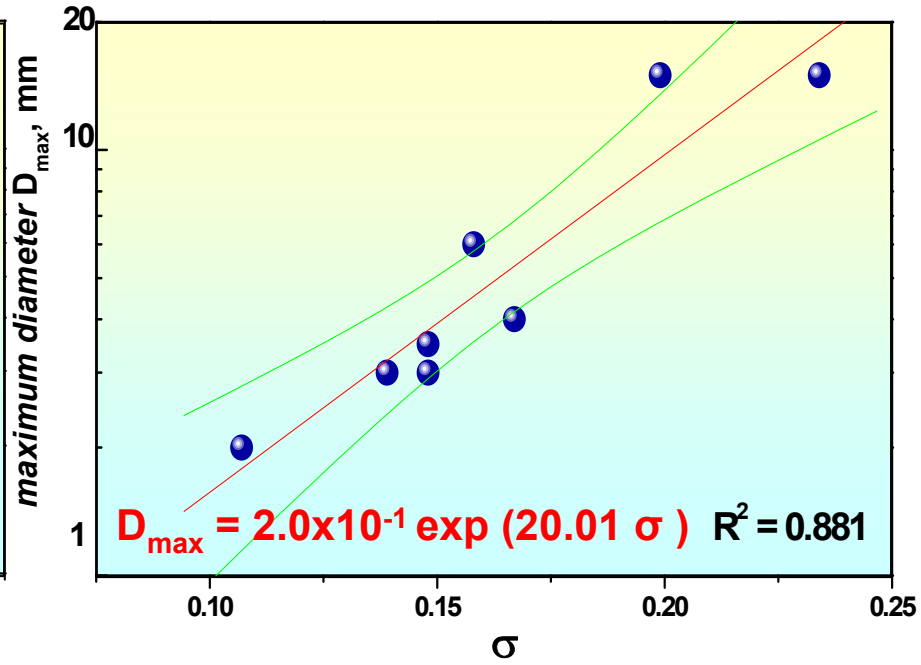
Calculation of G.F.A parameters

Ternary BMG system



3) Calculation of GFA parameters in ternary BMG alloy systems

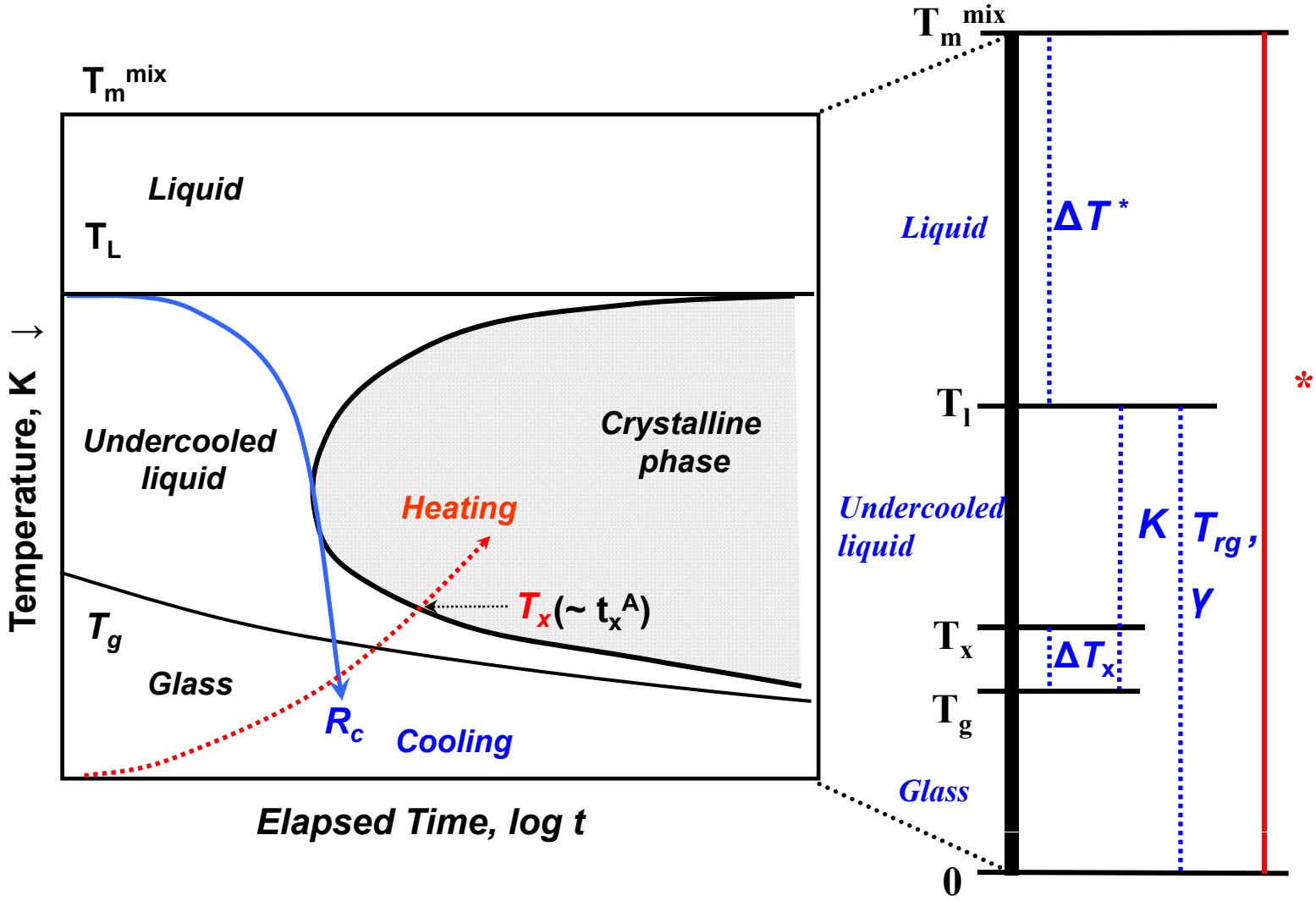




*** Sigma, σ parameter has a stronger correlation with GFA than other parameters suggested so far (ΔT_x: R^2=0.085, T_{rg}: R^2=0.567, K : R^2=0.136) in ternary BMG alloy systems.**

* Appl. Phys. Lett., 86, 061907 (2005)

Motivation for new criterion (1) : temperature range related with GFA parameters



Motivation for new criterion (2) : Role of characteristic temp. for GFA

Positive Temperature Factor		Negative Temperature Factor
T_x	ΔT_x ⟷	T_g
T_g	T_{rg} ⟷	T_l
$T_m^{mix} - T_l$	ΔT^* ⟷	T_m^{mix}
ΔT_x	K ⟷	$T_l - T_x$
T_x	γ ⟷	$T_l + T_g$

With T_x ↑and T_l ↓, GFA parameter ↑. But, the role of T_g is not consistent.

Role of T_g with respect to GFA : Two different viewpoints

- from thermodynamic consideration

γ : stability of metastable liquid for glass formation

$T_g \downarrow$ ➡ GFA ↑

- Stability of the liquid during undercooling (i.e. metastable state, T_g)
: Liquid with lower Tg has the potential to be undercooled to lower temp., inducing its higher stability.

- from kinetic consideration

- constant cooling to temp. below Tg

$$X(T) = \frac{4\pi}{3R^4}\int_{T_1}^{T_g} I(T')\left[\int_{T'}^{T_g} U(T'')\mathrm{d}T''\right]^3 \mathrm{d}T'$$

X(T) : time dependent volume fraction of crystalline phase

If glass formation : $X<10^{-6}$

$$R_c^4 = \frac{4\pi}{3\times 10^{-6}}\int_{T_1}^{T_g} I(T')\left[\int_{T'}^{T_g} U(T'')\mathrm{d}T''\right]^3 \mathrm{d}T'$$

I & U = the steady-state nucleation frequency and the crystal growth rate

$$I = \frac{10^{35}}{\eta}\exp\left[\frac{-16\pi}{3}\cdot\frac{\Delta S_f \alpha_m^3 T^2}{N_A k (T_1 - T)^2}\right]$$

and

$$U = \frac{kT}{3\pi a^2 \eta}\left[1-\exp\left(-\frac{(T_1 - T)\Delta S_f}{R_g T}\right)\right]$$

$1/R_c \propto$ increasing glass transition temp. Tg
viscosity of the supercooled liq.,
activation E for viscous flow, fusion entropy
decreasing liquidus temp. Tl

- T_{rg} : crystallization kinetics on GFA

$T_g \downarrow$ ➡ nucleation and growth rate ↑ -> GFA ↓

Points of issue for new GFA parameter

1. Combination of categories for glass formation

- γ parameter: thermodynamic/ kinetic aspects

➡ New parameter combining thermodynamic/ kinetic aspects

2. Temperature scale for GFA parameter

ΔT_x parameter : $T_x - T_g$

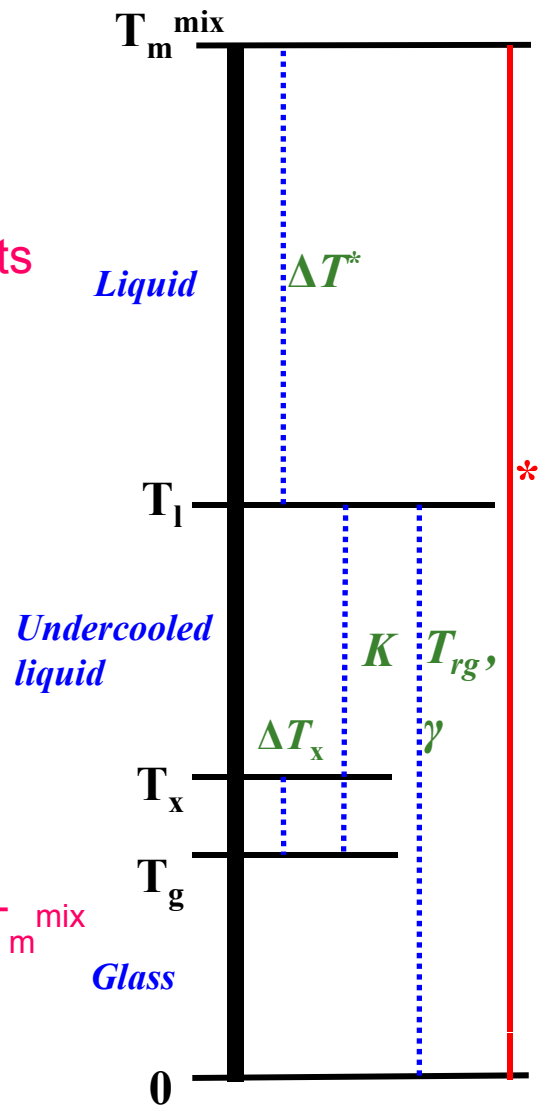
K parameter : $T_g - T_x - T_l$

T_{rg} parameter : $T_g - T_l$

γ parameter : $T_g - T_x - T_l$

ΔT^* parameter : $T_l - T_m^{mix}$

➡ New parameter covering temperature range $T_g - T_x - T_l - T_m^{mix}$ with considering about two different role of T_g



A new criterion for GFA : ε parameter

a. Liquid phase stability :

- Relative stability of stable liquid : distance from the T_m^{mix} to liquidus melting temp.,

$$\Delta T_m = T_m^{mix} - T_l$$ (γ parameter: T_l)

- Stability of metastable liquid : range of supercooled liquid,

$$\Delta T_x = T_x - T_g$$ (γ parameter: T_g)

b. Resistance to crystallization : T_x (γ parameter: T_x)

- relative difficulties for the formation (nucleation and crystal growth)

of the competing crystalline phases in various BMG forming alloy system

- Retarding incubation time for crystallization : relative position of the CCT curves along the time axis

c. nomalizing : T_m^{mix}

- Exclusion of systematic and compositional effects in various BMG alloy systems

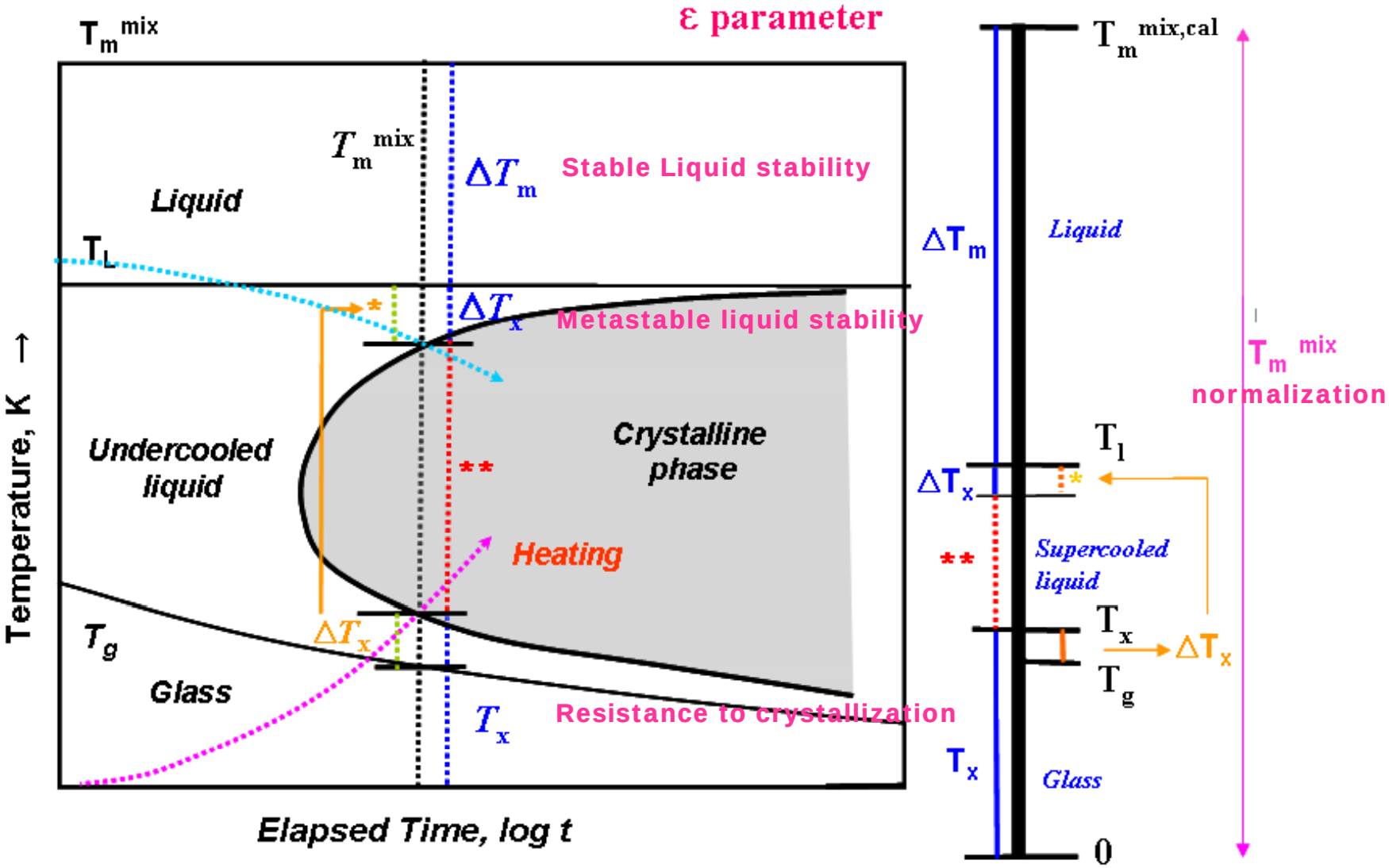
A New criterion for GFA of BMGs

$$\varepsilon = \frac{\Delta T_m + \Delta T_x + T_x}{T_m^{mix}}$$

E. S. Park et al., *submitted to Acta Mater.* (2005)

ε parameter (thermodynamic and kinetic aspects)

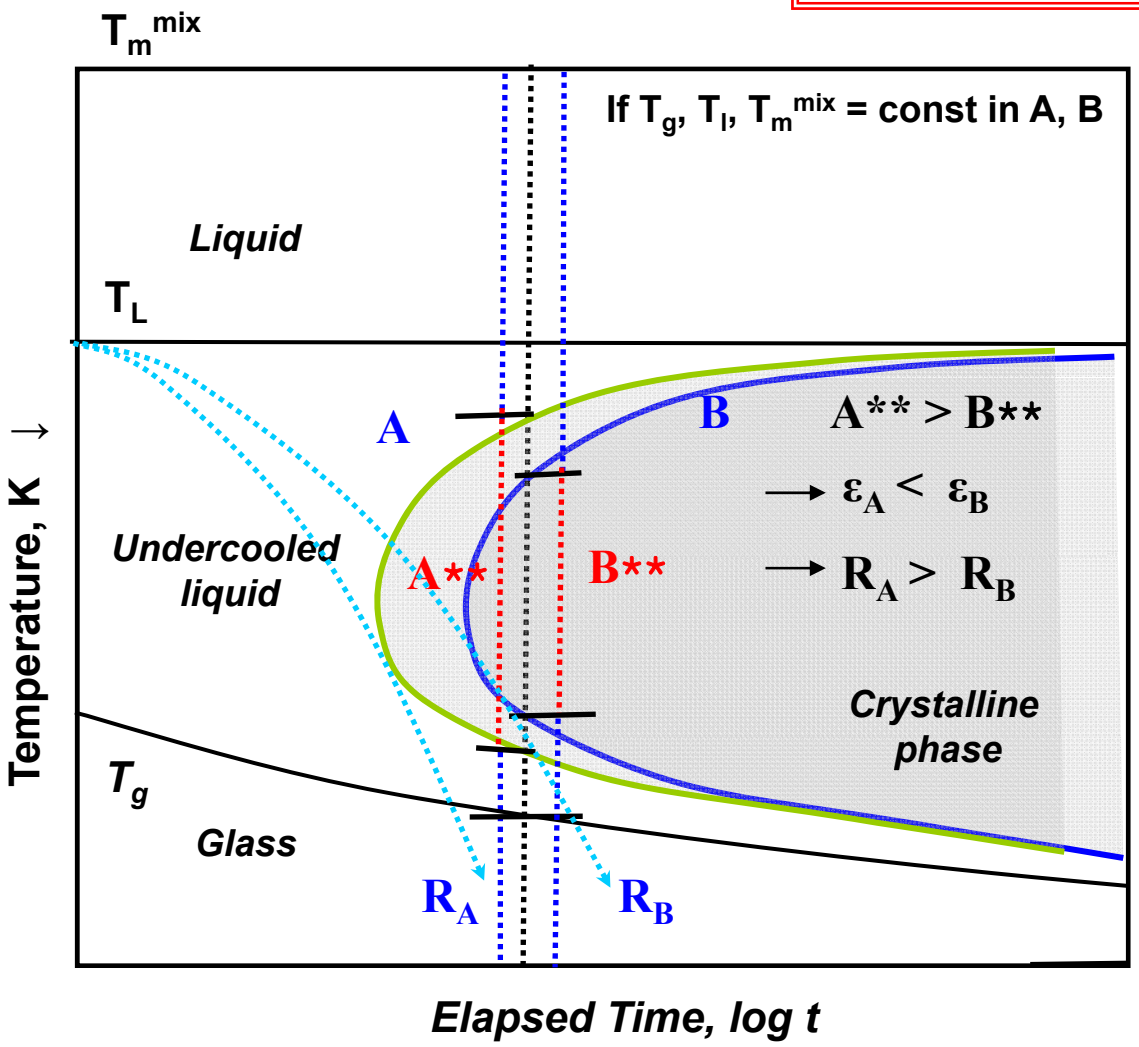
**** CCT curve showing temperature range for ε parameter***



ε parameter (thermodynamic and kinetic aspects)

A New criterion for GFA of BMGs

$$\varepsilon = \frac{\Delta T_m + \Delta T_x + T_x}{T_m^{mix}}$$



Cu-based

Cu-Zr
Cu-Zr-Al
Cu-Zr-Al-Al
Cu-Zr-Al-Y
Cu-Zr-Ti
Cu-Zr-Ti-Be
Cu-Zr-Ti-Ni-(Si,Sn)

Fe-based

Fe-B
Fe-Ni-B
Fe-Si-B
Fe-P-C
Fe-Nb-Y-B
Fe-Cr-Mo-C-B-(Y)

Mg-based

Mg-Ni-Nd
Mg-Cu-Y-(Ag)
Mg-Cu-Gd-(Ag)
Mg-Cu-Ag-Pd-Gd
Mg-Cu-Ni-Zn-Ag-Y-(Gd)

Ni-based

Ni-Nb
Ni-Nb-Ta
Ni-Nb-Ti-Hf
Ni-Si-B
Ni-Zr-Ti-(Sn-Si)
Ni-Zr-Ti-Si-Sn-Nb

Zr-based

Zr-Al-Ni
Zr-Al-Cu-Ni
Zr-Al-Cu-Ni-Ti
Zr-Be-Cu-Ni-Ti

Ca-based

Ca-Al
Ca-Al-Cu
Ca-Mg-Ni
Ca-Mg-Zn

Co-based

Co-Si-B
Co-Fe-Ta-B
Co-Fe-Nb-Zr-B

Nd-based

Nd-Al-Fe
Nd-Al-Ni-Cu-Co
Nd-Al-Ni-Cu-Fe

La-based

La-Al-Ni
La-Al-Cu
La-Al-Ni-Cu
La-Al-Ni-Co-Cu

Y-based

Y-Al-Co
Y-Al-Co-Sc
Y-Al-Co-Ni-Sc

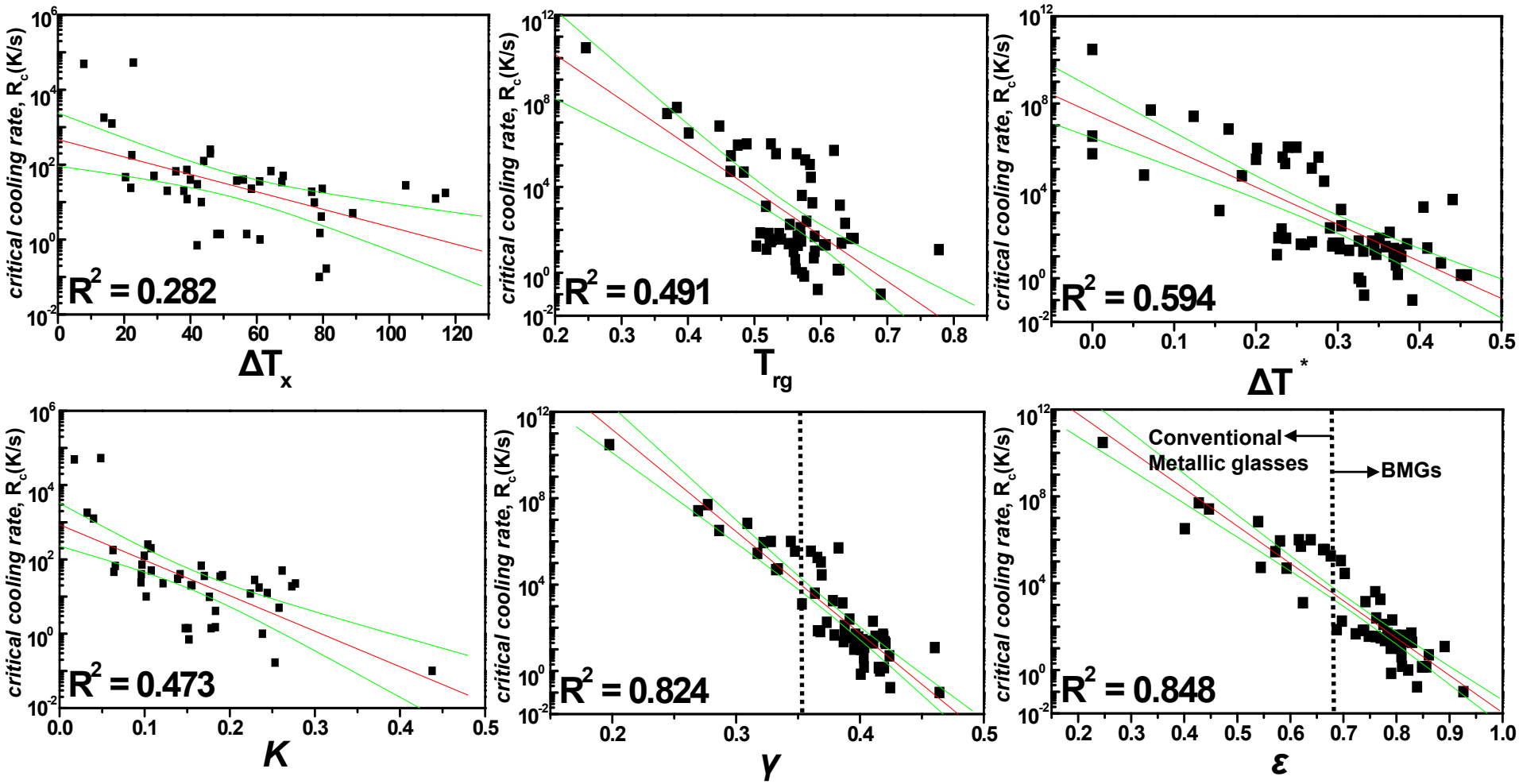
Pt-based

Pt-Ni-P
Pt-Cu-Ni-P
Pt-Cu-Co-P

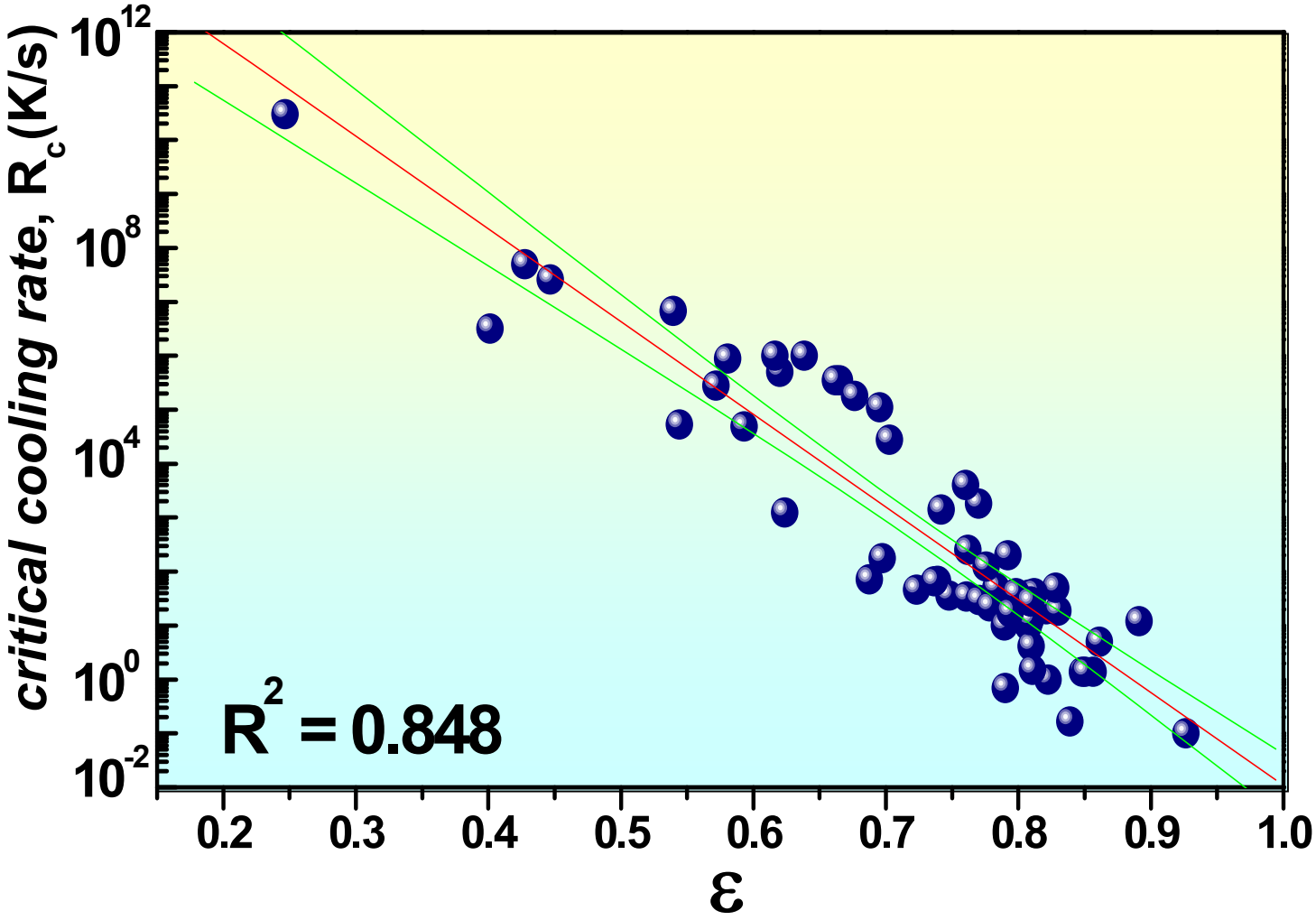
Pd-based

Pd-Si
Pd-Cu-Si
Pd-Ni-P
Pd-Cu-Ni-P

Critical cooling rate (R_c) vs. *GFA parameters*

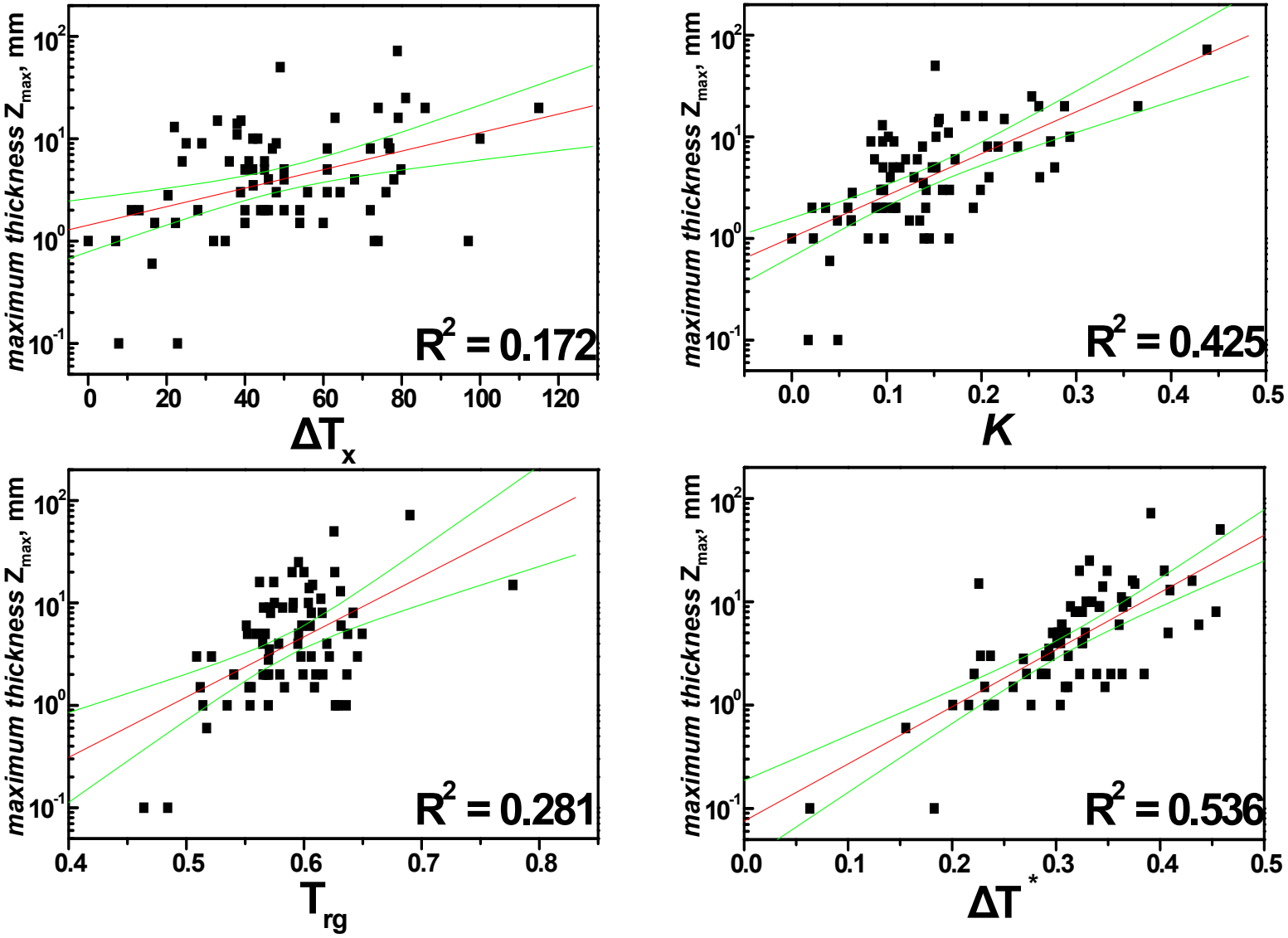


Correlation between R_c and ε parameter

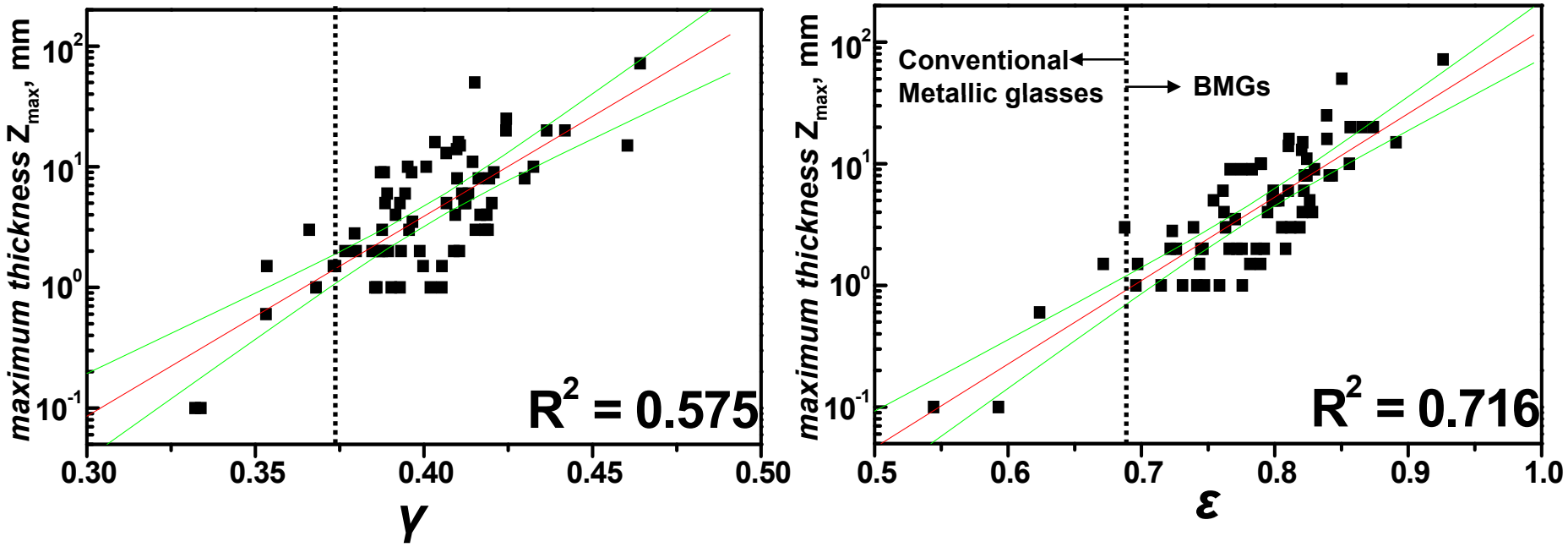


* Epsilon has a stronger correlation with R_c than other parameters suggested so far (ΔT_x: R^2=0.282, T_{rg}: R^2=0.491, ΔT^*: R^2=0.594, γ : R^2=0.824) in various BMG alloy systems.

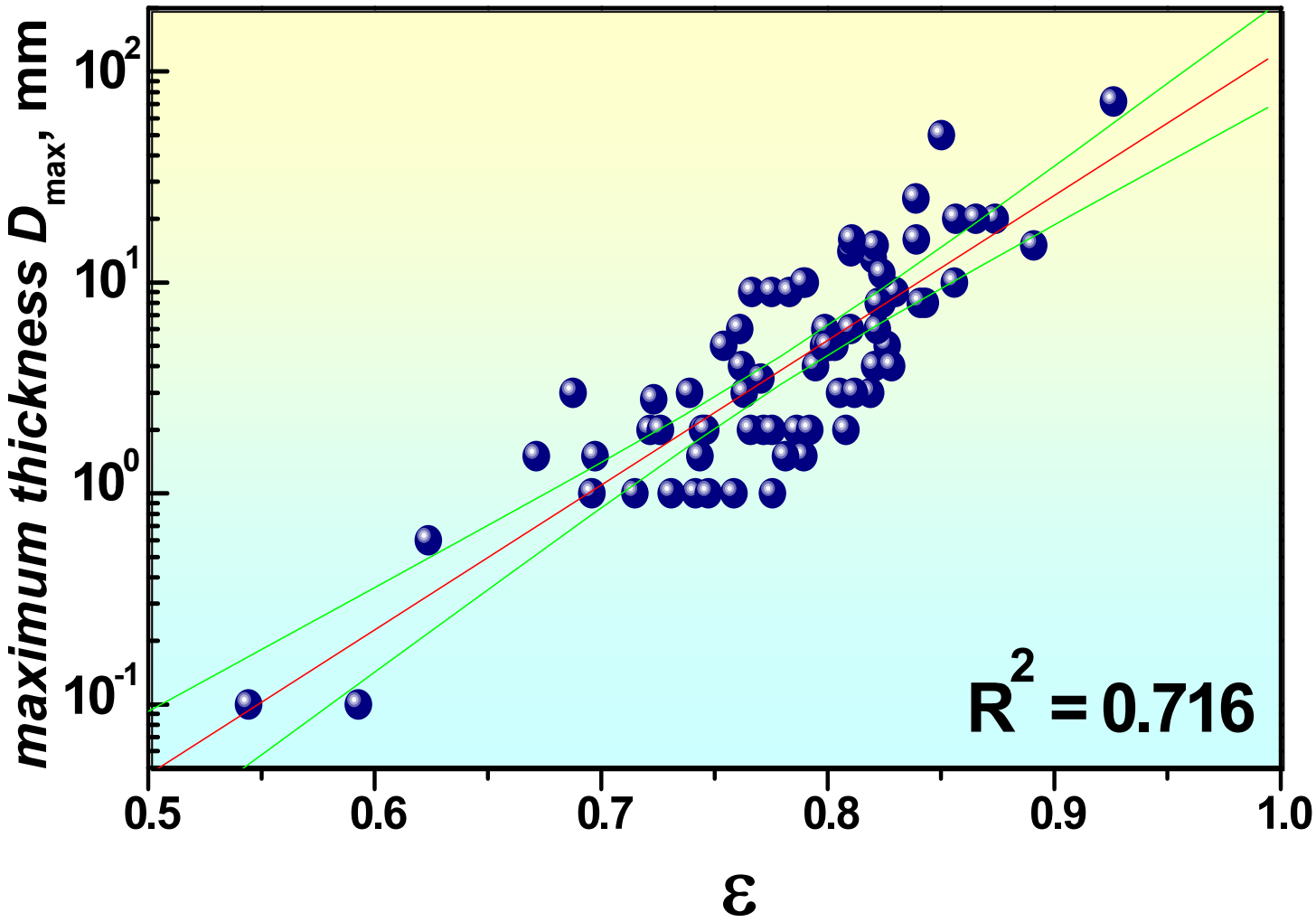
Maximum section thickness of BMGs (Z_{max}) vs. *GFA parameters*



Maximum section thickness of BMGs (Z_{max}) vs. GFA parameters



Correlation between D_{max} and ε parameter



- Epsilon parameter has a stronger correlation with D_{max} than other parameters suggested so far (ΔT_x: R^2=0.172, T_{rg}: R^2=0.281, ΔT^*: R^2=0.536, γ: R^2=0.536) in various BMG alloys.

Application of ε parameter

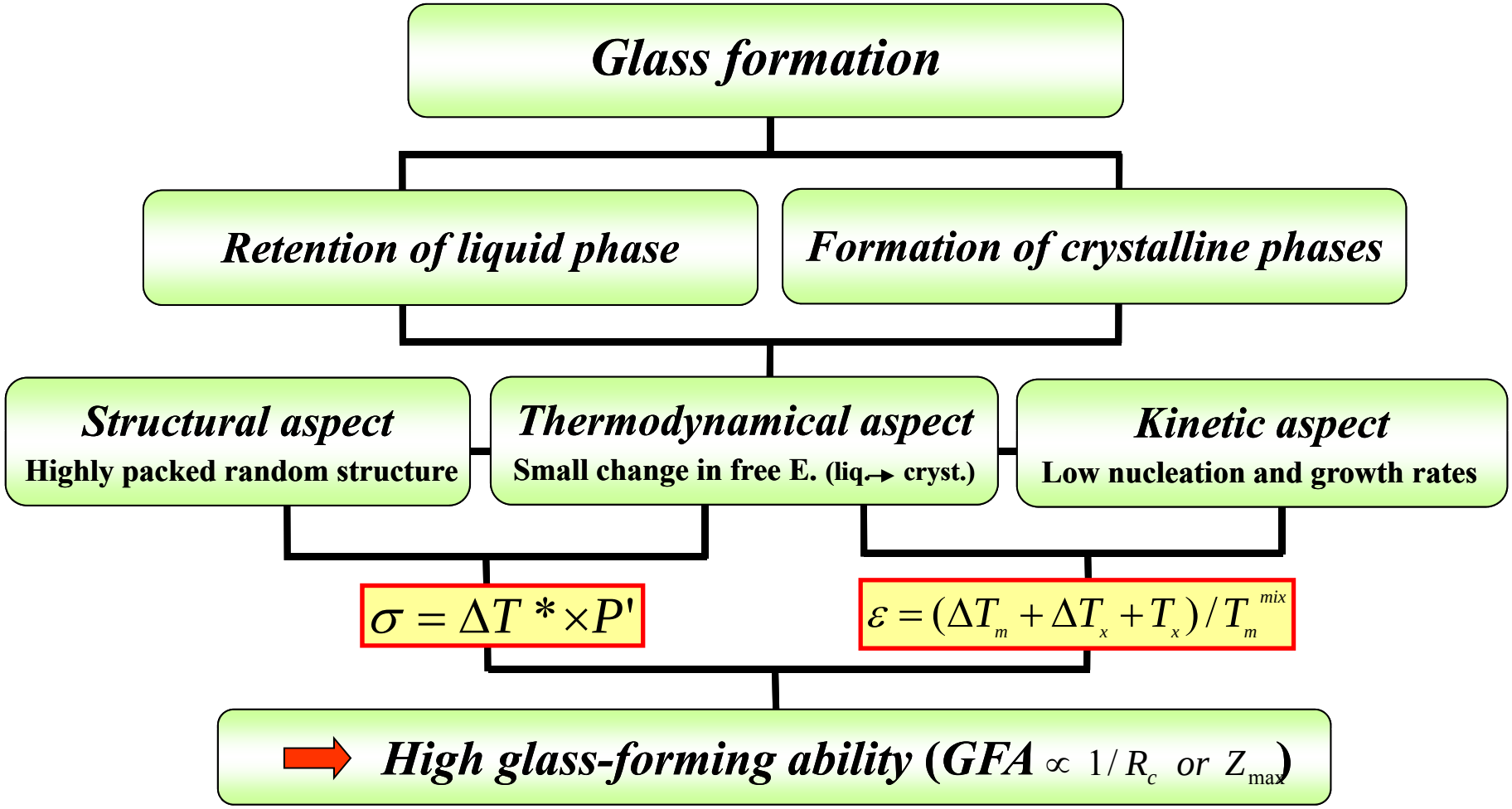
Estimation of the attainable maximum thickness for newly developed BMGs

*** Relationship between ε and maximum section thickness D_{max} :**

$$D_{max}(mm) = 1.71 \times 10^{-5} \exp(15.81\varepsilon)$$

	ΔT_x	T_{rg}	ΔT^*	K	γ	ε	$Z_{max, exp}$ (mm)	$Z_{max, cal}$ (mm)
$Ca_{66.4}Al_{33.6}$	7	0.627	0.201	0.023	0.390	0.715	1	1.4
$Ni_{60}Nb_{30}Ta_{10}$	13	0.599	0.287	0.021	0.380	0.726	2	1.7
$Fe_{74}Nb_6Y_3B_{17}$	48	0.597	0.290	0.094	0.396	0.763	3	2.9
$Ni_{59}Zr_{16}Nb_7Ti_{13}Si_3Sn_2$	40	0.650	0.302	0.096	0.412	0.798	5	5.1
$Ti_{45}Zr_5Ni_{15}Cu_{25}Be_7Sn_3$	61	0.595	0.328	0.152	0.407	0.800	5	5.3
$Cu_{54}Zr_{27}Ti_9Be_{10}$	42	0.637	0.310	0.114	0.412	0.801	5	5.3
$Mg_{65}Cu_{25}Gd_{10}$	61	0.572	0.325	0.238	0.416	0.822	8	7.5
$Cu_{46}Zr_{42}Al_7Y_5$	100	0.604	0.335	0.293	0.432	0.856	10	12.8
$Y_{36}Al_{24}Co_{20}Sc_{20}$	115	0.600	0.322	0.365	0.442	0.874	20	17.0

Improvement of GFA



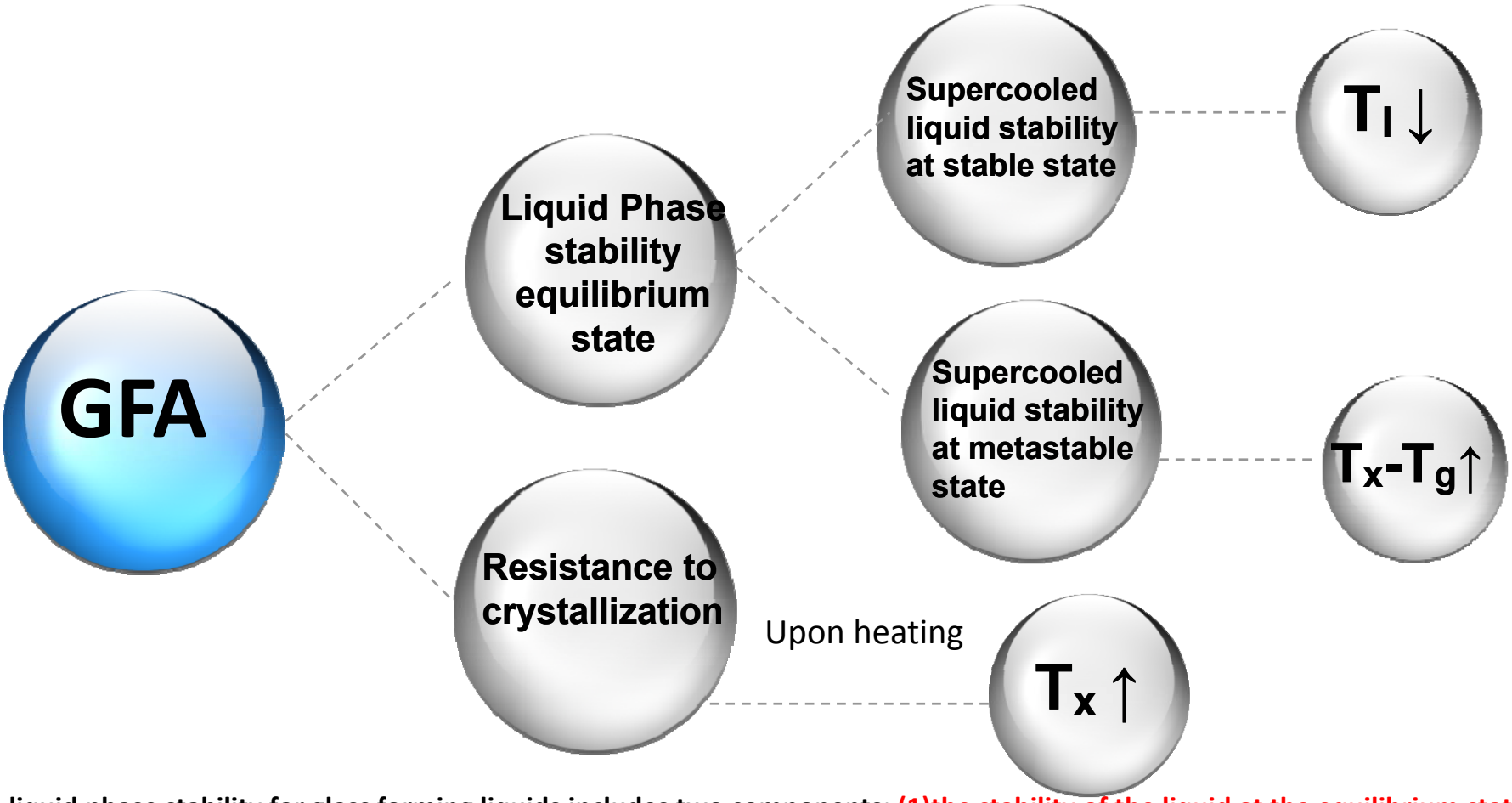
In estimating the GFA, the combinational effects of thermodynamic, kinetic and structural aspects for glass formation should be considered.

GFA Parameters *on the basis of thermodynamic or kinetic aspects*

GFA parameters	Expression	Year established	
T_{rg}	T_g / T_l	1969	D.Turnbull,Contemp.Phys.10(1969) 473
K	$(T_x-T_g) / (T_l-T_x)$	1972	A.Hruby, Czech. J.Phys. B 22 (1972) 1187
ΔT^*	$(T_m^{mix}-T_l) / T_m^{mix}$	1978	I.W.Donald, J.Non-Cryst.Solids 30 (1978) 77
ΔT_x	$T_x - T_g$	1993	A.Inoue, J.Non-Cryst.Solids 156-158(1993)473
γ	$T_x / (T_l+T_g)$	2002	Z.P.Lu, C.T.Liu, Acta Mater. 50 (2002) 3501
δ	$T_x / (T_l-T_g)$	2005	Q.J.Chen,Chiness Phys.Lett.22 (2005) 1736
α	T_x / T_l	2005	K.Mondal, J.Non-Cryst.Solids 351(2005) 1366
β	$T_x / T_g + T_g / T_l$	2005	K.Mondal, J.Non-Cryst.Solids 351(2005) 1366
φ	$(T_g / T_l)(T_x-T_g / T_g)^a$	2007	G.J.Fan,J.Non-Cryst. Solids 353 (2007) 102
γ_m	$(2T_x - T_g) / T_l$	2007	X.H.Du,J.Appl.phys.101 (2007) 086108
β	$(T_g / T_l- T_g)(T_g / T_l- T_g)$	2008	Z.Z.Yuan, J. Alloys Compd.459 (2008)
ξ	$\Delta T_x / T_x + T_g / T_l$	2008	X.H.Du,Chinese Phys.B 17(2008) 249

$\gamma_m = (2T_x - T_g) / T_l$

understanding of the new modified parameter γ_m



The liquid phase stability for glass forming liquids includes two components: (1)the stability of the liquid at the equilibrium state, (stable state) and (2)the stability of the liquid during undercooling (metastable state). The liquid phase stability can be measured by the magnitude of $(T_l+T_g)/2$, which is the average of the stability of the liquids at equilibrium and metastable state.