SPECIAL TOPIC — Amorphous physics and materials

# LaGa-based bulk metallic glasses*

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We report the formation of LaGa-based bulk metallic glasses. Ternary La–Ga–Cu glassy rods of 2–3 mm in diameter can be easily formed in a wide composition range by the conventional copper mold casting method. With minor addition of extra elements such as Co, Ni, Fe, Nb, Y, and Zr, the critical diameter of the full glassy rods of the La–Ga–Cu matrix can be markedly enhanced to at least 5 mm. The characteristics and properties of these new LaGa-based bulk metallic glasses with excellent glass formation ability and low glass transition temperature are model systems for fundamental issues investigation and could have some potential applications in micromachining field.

**Keywords:** bulk metallic glasses, glass forming ability, La–Ga–Cu alloys

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## 1. Introduction

Bulk metallic glasses (BMGs) are considered to be useful in a wide range of potential applications because their unique properties, including high strength, large elastic strain limit, high hardness, and good soft magnetic properties, which have attracted more and more attention.[1–4] In the past few decades, a lot of glass-forming alloys with excellent glass-forming abilities have been successfully developed in Zr-,[5,6] Pd-,[7,8] Fe-,[9,10] Ni-,[11,12] Ti-,[13] Cu-,[14,15] Al-,[16] Mg-,[17] Cr-,[18] U-,[19] and rare earth (RE)-based[20–33] systems, which has significantly broadened the promise of amorphous alloys.

Recently, with the development of the imprinting, embossing, and molding techniques using the viscous flow workability to make micro- and nano-devices from BMGs,[34] intensive interest has been focused on developing BMGs with low glass transition temperature ($T_g$), high glass-forming ability (GFA), wide supercooled liquid region ($\Delta T_x = T_x - T_g$, $T_x$ represents the crystallization temperature), high stability, and good mechanical properties. Besides, BMGs with lower $T_g$ can provide a model system to investigate the slow dynamic and flow behaviors near room temperature of metallic amorphous. Recently, Ce-,[20–22] Yb-,[31] Sr-,[35,36] CaLi-,[37] Zn-,[38] and Au-based[39] BMGs with an exceptionally low $T_g$ close to room temperature have been developed. However, these MGs with low $T_g$ are too expensive or easily oxidized or react with the water quickly. So it is necessary to develop some new low cost BMGs with strong oxidation resistance, high corrosion resistance, and low $T_g$.

Gallium (Ga) is an element with low density (5.904 g/cm$^3$), low elastic moduli (its Young's modulus is 9.8 GPa), low melting point (303 K), and strong oxidation resistance. Considering the similarities of atomic radius and atomic electronic negativity between Al and Ga elements, the Ga element is always used to substitute the Al element.[40–44] According to the elastic moduli criterion,[45] the metallic glasses with the substitution of Al by Ga could have low $T_g$ and unique mechanical and physical properties.[40–44]

In this work, we report the formation of La–Ga–Cu bulk metallic glasses with low $T_g$ and high glass-forming ability. By selecting appropriate minor additions of elements $M$ ($M$ represents a series of elements such as Co, Ni, Fe, Nb, Y, and Zr), the critical diameter of the full glassy rods of the La–Ga–Cu–$M$ can be markedly enhanced to at least 5 mm. The characteristics and properties of these new LaGa-based BMGs are studied and compared.

## 2. Experiment

The ingots of the studied alloys in nominal composition of La–Ga–Cu and La–Ga–Cu–$M$ ($M$ = Co, Ni, Fe, Nb, Y, Si, and Zr) were prepared by arc melting the constituent elements in a Ti-gettered argon atmosphere. The cylindrical samples with the diameter of 2 mm, 3 mm, or 5 mm were fabricated by the copper mold casting method and listed in Table 1. The amorphous nature of the as-cast alloys was ascertained using x-ray diffraction (XRD) with a MAC M03 XHF diffractometer with Cu $K_\alpha$ radiation and high-resolution transmission electron microscopy (HRTEM) using a TECNAIF20 instrument operated at 200 kV. Thermal analysis was carried out using differential scanning calorimetry (DSC; Perkin-Elmer DSC-8000) at a heating rate of 20 K/min. The density was determined by the Archimedean technique with an accuracy of within 0.1%. Elastic constants of the BMGs, including Yong's modulus $E$, shear modulus $G$, Poisson's ratio $\nu$, and bulk modulus $K$ were measured using resonant ultrasound spectroscopy (RUS).

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**Table 1.** Thermal properties (heating rate 20 K/min) and room temperature density of LaGa-based MGs.

| Composition | $D$/mm | $T_g$/K | $T_x$/K | $\Delta T_x$/K | $T_m$/K | $T_l$/K | $T_{rg}(T_g/T_l)$ | $\gamma[T_x/(T_g+T_l)]$ | $\rho$/g·cm$^{-3}$ |
|---|---|---|---|---|---|---|---|---|---|
| $La_{68}Ga_{10}Cu_{22}$ | 2 | 375 | 424 | 49 | 694 | 722 | 0.519 | 0.387 | 6.447 |
| $La_{68}Ga_{12}Cu_{20}$ | 2 | 380 | 432 | 52 | 690 | 713 | 0.533 | 0.395 | 6.467 |
| $La_{68}Ga_{14}Cu_{18}$ | 2 | 391 | 435 | 44 | 691 | 715 | 0.547 | 0.393 | 6.437 |
| $La_{70}Ga_{10}Cu_{20}$ | 2 | 379 | 409 | 30 | 695 | 733 | 0.517 | 0.368 | 6.433 |
| $La_{70}Ga_{12}Cu_{18}$ | 3 | 382 | 438 | 56 | 687 | 720 | 0.531 | 0.397 | 6.431 |
| $La_{70}Ga_{14}Cu_{16}$ | 2 | 394 | 433 | 39 | 692 | 762 | 0.517 | 0.375 | 6.486 |
| $La_{70}Ga_{16}Cu_{14}$ | 2 | 401 | 452 | 51 | 685 | 727 | 0.552 | 0.401 | 6.391 |
| $La_{72}Ga_{12}Cu_{16}$ | 2 | 384 | 406 | 22 | 694 | 752 | 0.511 | 0.357 | 6.388 |
| $La_{72}Ga_{14}Cu_{14}$ | 3 | 388 | 450 | 62 | 681 | 735 | 0.528 | 0.401 | 6.441 |
| $La_{69.5}Ga_{12}Cu_{18}Co_{0.5}$ | > 5 | 394 | 482 | 88 | 685 | 704 | 0.560 | 0.439 | 6.426 |
| $La_{69}Ga_{12}Cu_{18}Co_1$ | > 5 | 397 | 485 | 88 | 685 | 710 | 0.559 | 0.438 | 6.439 |
| $La_{68}Ga_{12}Cu_{18}Co_2$ | > 5 | 398 | 480 | 82 | 685 | 714 | 0.557 | 0.432 | 6.452 |
| $La_{67}Ga_{12}Cu_{18}Co_3$ | > 5 | 398 | 486 | 88 | 682 | 716 | 0.556 | 0.436 | 6.465 |
| $La_{66}Ga_{12}Cu_{18}Co_4$ | > 5 | 402 | 487 | 85 | 683 | 725 | 0.554 | 0.432 | 6.483 |
| $La_{65}Ga_{12}Cu_{18}Co_5$ | > 5 | 405 | 480 | 75 | 682 | 733 | 0.553 | 0.422 | 6.498 |
| $La_{68}Ga_{12}Cu_{18}Fe_2$ | > 5 | 388 | 455 | 67 | 687 | 742 | 0.523 | 0.403 | 6.422 |
| $La_{68}Ga_{12}Cu_{18}Ni_2$ | > 5 | 400 | 472 | 72 | 690 | 725 | 0.552 | 0.420 | 6.447 |
| $La_{68}Ga_{12}Cu_{18}Nb_2$ | > 5 | 395 | 466 | 71 | 691 | 748 | 0.528 | 0.408 | 6.533 |
| $La_{68}Ga_{12}Cu_{18}Si_2$ | 3 | 408 | 479 | 71 | 693 | 718 | 0.568 | 0.425 | 6.384 |
| $La_{68}Ga_{12}Cu_{18}Zr_2$ | > 5 | 392 | 471 | 79 | 685 | 710 | 0.552 | 0.427 | 6.435 |
| $La_{68}Ga_{12}Cu_{18}Y_2$ | > 5 | 387 | 448 | 61 | 684 | 706 | 0.548 | 0.410 | 6.416 |

## 3. Results and discussion

Figure 1 shows the ternary phase diagram for the composition region of the La–Ga–Cu BMGs. Nine typical bulk glass alloys (filled circles), which can be quenched into a fully glassy state rod of 2–3 mm in diameter, are located in the region. One can see that BMGs with a wide composition range of 68–72 at.% La, 10–16 at.% Ga, and 14–22 at.% Cu can be easily prepared by the copper mold casting method. The $La_{70}Ga_{12}Cu_{18}$ and $La_{72}Ga_{14}Cu_{14}$BMGs are the best glass formers in present La–Ga–Cu alloys, the critical diameter can reach about 3 mm. Figure 2(a) shows the XRD patterns of the typical as-cast La–Ga–Cu samples, the broad diffraction maxima indicating the fully gassy structure of the alloys. Figure 2(b) presents the HRTEM image and selected-area electron diffraction (SAED) pattern (the inset image of Fig. 2(b)) of the as-cast $La_{70}Ga_{12}Cu_{18}$ rod with a diameter of 3 mm. Both of the homogeneous contrast in the HRTEM image and only a broad halo ring in the SAED pattern confirm the amorphous structure of the alloy. Figure 3(a) shows that the DSC curves of the as-cast samples have distinct glass transition and sharp crystallization peaks, further confirming the amorphous structure.

From the DSC traces in Figs. 3(a) and 3(b), the $T_g$, the onset temperature of crystallization $T_x$, the melting temperature $T_m$, the liquid temperature $T_l$, and the supercooled liquid temperature range $\Delta T_x = T_x - T_g$ of the ternary La–Ga–Cu BMGs are determined and listed in Table 1. As shown in Table 1 and Fig. 3(a), $La_{68}Ga_{10}Cu_{22}$ has the lowest $T_g$ of 375 K among these ternary La–Ga–Cu BMGs, and the $T_g$ increases from 379 K to 401 K with increasing Ga content from 10 at.% to 16 at.% in the $La_{70}Ga_{10+x}Cu_{20-x}$ and $La_{72-x}Ga_{12}Cu_{16+x}$ systems, indicating that lower Ga content or higher Cu content results in lower $T_g$. Generally, the LaGa-based BMGs have exceptionally low $T_g$ (375–401 K) close to that of many polymeric glasses such as PVC (348–378 K).[46]

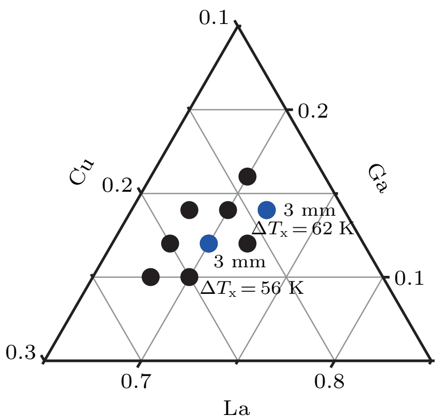


**Fig. 1.** (color online) Ternary phase diagram shows the composition region of La–Ga–Cu BMGs.

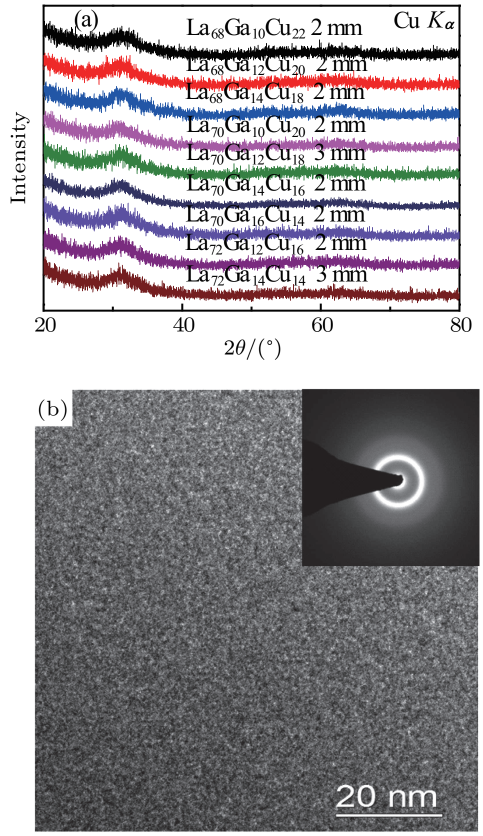


**Fig. 2.** (color online) (a) XRD patterns of the as-cast rods of La–Ga–Cu BMGs with the different diameters; (b) the HRTEM image and SAED pattern (the inset image) of the as-cast $La_{70}Ga_{12}Cu_{18}$ sample of 3 mm.

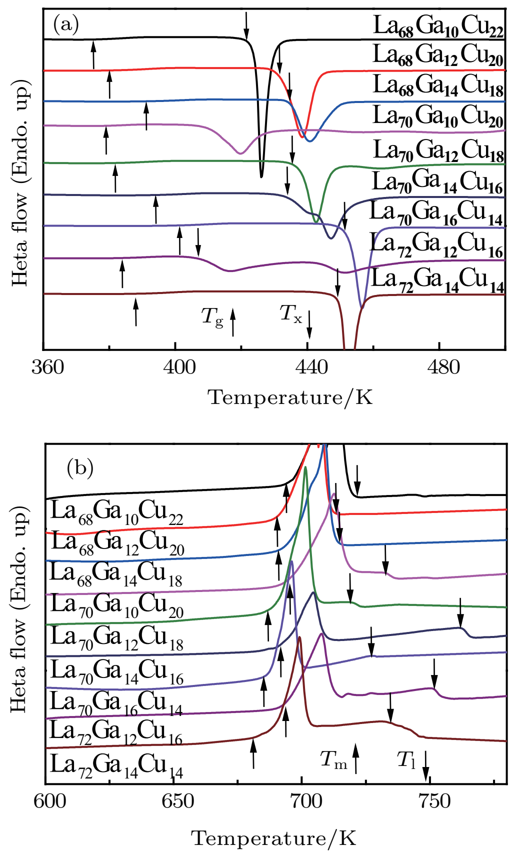


**Fig. 3.** (color online) DSC traces concentrated on the glass transition (a) and melting (b) for the typical La–Ga–Cu BMGs at a heating rate of 20 K/min.

Minor alloying addition has shown dramatic effects on glass formation and various properties of bulk metallic glasses.[47–53] To further improve the GFA of ternary $La_{72}Ga_{10}Cu_{18}$ alloy, a series of elements with different atomic sizes were selected to add into the alloy. According to the atomic radius, these elements can be classified into three groups: large atoms (Goldschmidt radii: Y, 0.182 nm; Zr, 0.16 nm), intermediate atoms (Nb, 0.147 nm; Fe, 0.126 nm; Co, 0.125 nm; Ni, 0.125 nm), and small atoms (Si, 0.115 nm).[47] Figure 4(a) shows the XRD patterns of the as-cast rods of $La_{70-x}Ga_{12}Cu_{18}Co_x$ ($x = 0.5$, 1, 2, 3, 4, 5) with the diameter of 5 mm, and figure 4(b) shows the XRD patterns of $La_{68}Ga_{12}Cu_{18}M_2$ ($M$ = Fe, Co, Ni, Zr, Nb, Si, Y) BMGs with the different diameters. The XRD patterns of the as-cast alloys exhibit only broad diffraction peaks typical for an entirely amorphous structure. From the DSC traces in Fig. 5, the $T_g$, $T_x$, $T_m$, $T_l$, and $\Delta T_x = T_x - T_g$ of the ternary La–Ga–Cu–$M$ ($M$ represents addition elements) BMGs are determined and listed in Table 1. Besides, the critical diameters $D_c$ of the fully glassy La–Ga–Cu–$M$ alloys are also listed in Table 1.

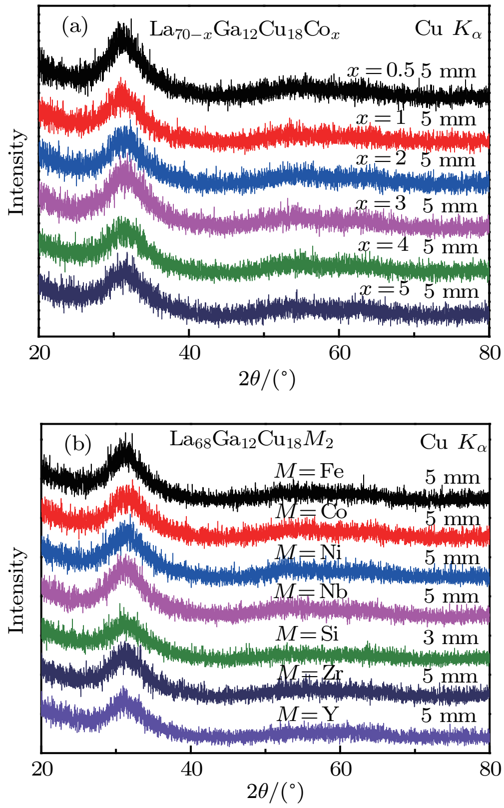


**Fig. 4.** (color online) XRD patterns of the as-cast rods of (a) $La_{70-x}Ga_{12}Cu_{18}Co_x$ ($x = 0.5$, 1, 2, 3, 4, 5) and (b) $La_{68}Ga_{12}Cu_{18}M_2$ ($M$ = Fe, Co, Ni, Zr, Nb, Si, Y) BMGs with different diameters.

From Table 1, we find experimentally that both the large and the intermediate atoms even with minor addition have great positive effect on the GFA of the ternary $La_{72}Ga_{10}Cu_{18}$ alloys. Replacing 2 at.% La with Fe, Ni, Nb, Zr, or Y, the $D_c$ of $La_{72}Ga_{10}Cu_{18}$ is drastically enhanced from 3 mm to at least

5 mm. For Co, even a minor addition of 0.5 at.% can greatly improve the GFA of $La_{72}Ga_{10}Cu_{18}$ from 2 mm to at least 5 mm. However, the small atoms have no obviously positive effect on GFA. Substituting 2% La with Si in $La_{72}Ga_{10}Cu_{18}$, the GFA of $La_{72}Ga_{10}Cu_{18}$ is not obviously increased. These results are quite different from those of the previous studies, where more than 2% additions of Si in Cu-based alloys were detrimental to the GFA.[54]

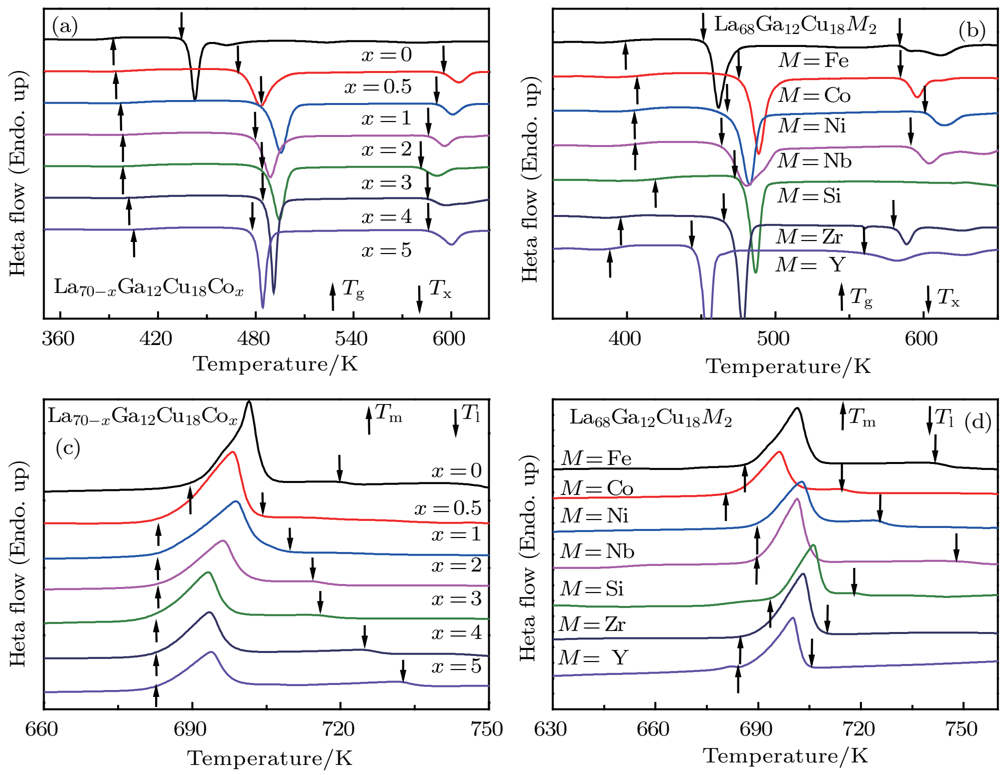


**Fig. 5.** (color online) DSC traces concentrated on the glass transition (a), (b) and melting (c), (d) for the typical La–Ga–Cu–$M$ ($M$ = Fe, Co, Ni, Zr, Nb, Si, Y) BMGs at a heating rate of 20 K/min.

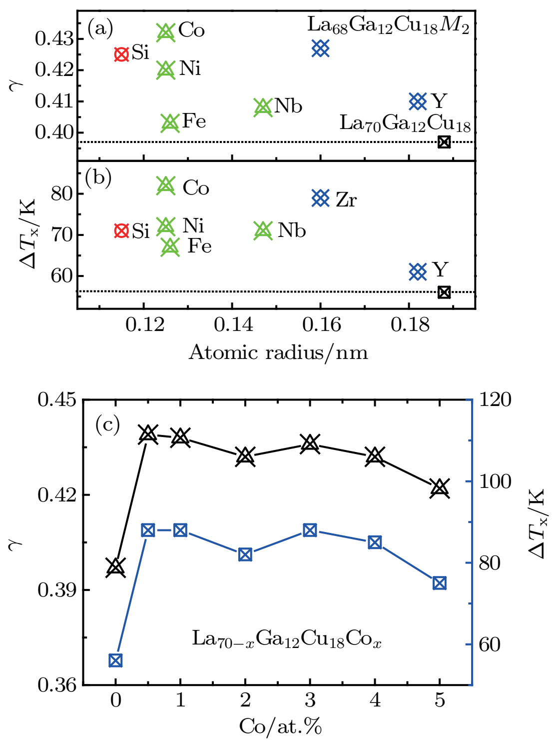


**Fig. 6.** (color online) Relationship between the atomic radius and (a) the glass forming ability parameter $\gamma$ and (b) thermal stability parameter $\Delta T_x$. (c) Relationship between $\gamma$ or $\Delta T_x$ and Co additive content.

Both of glass-forming ability and thermal stability are important parameters for machining in the supercooled liquid region. We choose the thermodynamic parameter $\gamma = T_x/(T_g + T_l)$ to characterize the GFA, and $\Delta T_x = T_x - T_g$ to characterize the thermal stability. Figures 6(a) and 6(b) show the effect of minor alloying on the GFA and thermal stability. We can find that after minor alloying, both $\gamma$ and $\Delta T_x$ increase, which confirms that minor alloying is an effective method for improving the GFA and thermal stability of the alloy system. Figure 6(c) shows the effect of Co additive content on $\gamma$ and $\Delta T_x$. It can be seen that both $\gamma$ and $\Delta T_x$ show a "Λ" shape relationship with the additive content. Such a phenomenon is rarely seen in the known metallic glasses and contrasts with previous findings that the beneficial addition of transition metals to improve GFA is usually higher than 3 at.%.[42]

To further understand the mechanism of glass transition and evaluate the GFA of the La–Ga–Cu alloy, we study its crystallization behavior by using DSC. Figure 7 shows the DSC curves of the $La_{70}Ga_{12}Cu_{18}$ BMG at different heating rates. The crystallization peak shifts to higher temperature with increasing heating rate as shown in Fig. 7, indicating the obvious kinetic behavior of crystallization. The inset shows the dependence of $T_g$ and $T_x$ upon $\phi$ at different heating rates from 5 K/min to 160 K/min. The crystallization kinetics of the MGs can be evaluated by Kissinger's equation[55]

$$\ln\frac{T^2}{\phi}=\frac{E_a}{T}+\ln\frac{E_a}{k_B K_0},$$

where $T$ is the crystallization characteristic temperature, $k_B$ is the Boltzman constant, $K_0$ is the frequency factor, and $E_a$ is the apparent activation energy. From the data inset, the activation energy of crystallization is evaluated to be about 1.61 eV, which is fairly small compared with that of other MGs.[56]

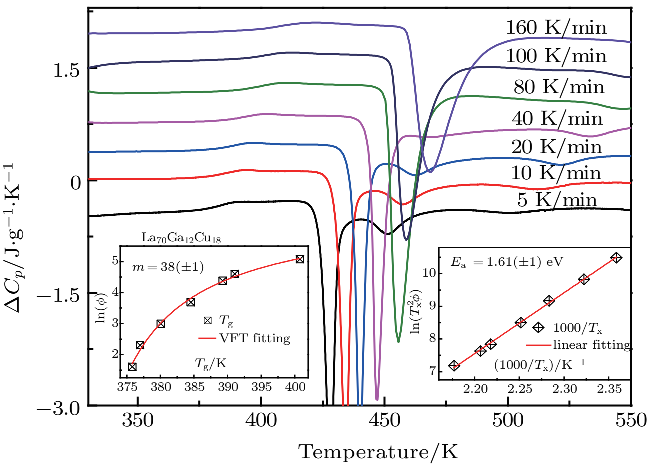


**Fig. 7.** (color online) DSC traces of $La_{70}Ga_{12}Cu_{18}$ BMG at different heating rates from 5 K/min to 80 K/min. The inset shows the Kissenger plot of $T_x$ and VFT relationship between $T_g$ and $\phi$.

Fragility shows the intrinsic features of the supercooled liquid and can be used to classify glass-forming liquid into three general categories: strong, intermediate, and fragile. The fragility can be quantified by the fragility parameter $m$ defined as[57]

$$m=\left.\frac{\mathrm{d}\log\langle\tau\rangle}{\mathrm{d}l\langle T_g/T\rangle}\right|_{T=T_g},$$

where $\langle\tau\rangle$ is the average relaxation time, and $T$ is the temperature. From the VFT fit, the $m$ at a particular $T_g$ can be calculated from[58]

$$m=\frac{DT_0T_g}{(T_g-T_0)^2\ln 10}.$$

From the data inset, the fragility $m$ can be evaluated to be about 38±1, which is very close to the strong limit and similar to that of Pr-, La-, Tm-, and Mg-based MGs.[56,59]

A lot of features and properties of metallic glasses correlate remarkably well with the elastic modulus.[60,61] We also study the elastic properties of LaGa-based BMGs by using the resonant ultrasound spectroscopy (RUS) and the results are shown in Table 2. Figure 8(a) shows the various BMGs in the form of Poisson's ratio versus fragility of the glass-forming liquid. There is a clear linear relationship between $m$ and possion's ratio, which is matched with the results of Novikov.[60] Figure 8(b) shows the various BMGs in the form of $T_g$ versus $E$. There is a clear linear relationship between $T_g$ and $E$. From the data in Fig. 8(b), we confirm that the obtained LaGa-based BMGs have lower elastic modulus and lower $T_g$ compared with other BMGs.

**Table 2.** The elastic constants of La–Cu–Ga–$M$ MGs.

| Composition | $E$/GPa | $G$/GPa | $K$/GPa | $\gamma$ |
|---|---|---|---|---|
| $La_{68}Ga_{10}Cu_{22}$ | 31.9 | 11.8 | 40.8 | 0.352 |
| $La_{68}Ga_{12}Cu_{20}$ | 32.2 | 11.9 | 40.5 | 0.353 |
| $La_{68}Ga_{14}Cu_{18}$ | 32.7 | 12.1 | 41.5 | 0.351 |
| $La_{70}Ga_{10}Cu_{20}$ | 31.5 | 11.6 | 40.4 | 0.357 |
| $La_{70}Ga_{12}Cu_{18}$ | 31.9 | 11.8 | 40.1 | 0.352 |
| $La_{70}Ga_{14}Cu_{16}$ | 32.6 | 12.1 | 41.8 | 0.347 |
| $La_{70}Ga_{16}Cu_{14}$ | 32.7 | 12.2 | 41.2 | 0.341 |
| $La_{72}Ga_{12}Cu_{16}$ | 31.4 | 11.5 | 39.8 | 0.365 |
| $La_{72}Ga_{14}Cu_{14}$ | 32.3 | 11.9 | 41.3 | 0.357 |
| $La_{69.5}Ga_{12}Cu_{18}Co_{0.5}$ | 32.1 | 11.9 | 40.3 | 0.349 |
| $La_{69}Ga_{12}Cu_{18}Co_1$ | 32.2 | 11.9 | 40.5 | 0.353 |
| $La_{68}Ga_{12}Cu_{18}Co_2$ | 32.4 | 12.0 | 40.7 | 0.350 |
| $La_{67}Ga_{12}Cu_{18}Co_3$ | 32.6 | 12.1 | 40.9 | 0.347 |
| $La_{66}Ga_{12}Cu_{18}Co_4$ | 32.7 | 12.1 | 41.0 | 0.351 |
| $La_{65}Ga_{12}Cu_{18}Co_5$ | 32.8 | 12.1 | 41.2 | 0.355 |
| $La_{68}Ga_{12}Cu_{18}Fe_2$ | 33.4 | 12.3 | 41.6 | 0.358 |
| $La_{68}Ga_{12}Cu_{18}Ni_2$ | 33.4 | 12.4 | 41.2 | 0.347 |
| $La_{68}Ga_{12}Cu_{18}Nb_2$ | 32.9 | 12.2 | 40.9 | 0.348 |
| $La_{68}Ga_{12}Cu_{18}Si_2$ | 32.2 | 11.9 | 40.3 | 0.353 |
| $La_{68}Ga_{12}Cu_{18}Zr_2$ | 32.5 | 12.1 | 40.5 | 0.343 |
| $La_{68}Ga_{12}Cu_{18}Y_2$ | 32.3 | 12.0 | 40.4 | 0.346 |

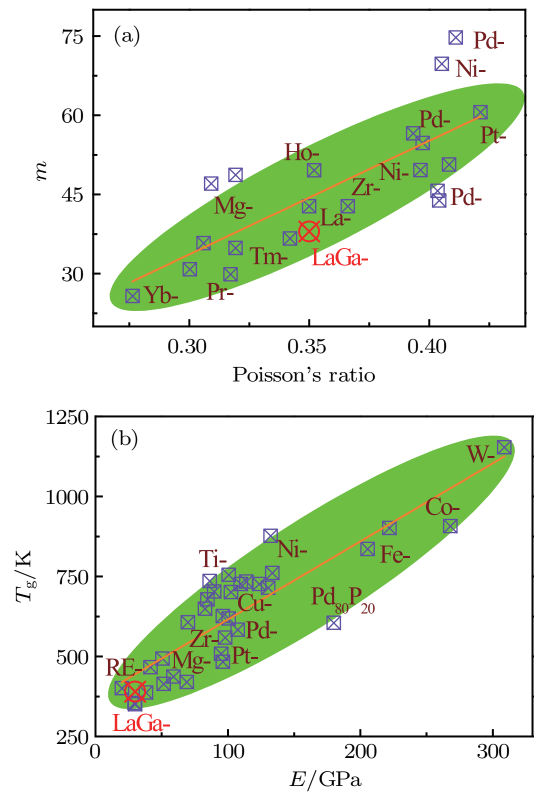


**Fig. 8.** (color online) (a) A linear relationship between the fragility $m$ of metallic glass-forming liquids and the Poisson's ratio of BMGs. (b) A linear relationship between $T_g$ and $E$.

## 4. Conclusion

In summary, we report the formation of LaGa-based bulk metallic glasses with extremely low $T_g$, high glass-forming ability, wide supercooled liquid region, high stability, and good properties. The LaGa-based MGs with excellent glass formation ability and extremely low glass transition temperatures could have potential applications in micromachining field.

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## References


[1] Johnson W L 1999 *MRS Bull.* **24** 42
[2] Inoue A 2000 *Acta Mater.* **48** 279
[3] Wang W H, Dong C and Shek C H 2004 *Mater. Sci. Eng. R.* **44** 45
[4] Greer A L and Ma E 2007 *MRS Bull.* **32** 611
[5] Inoue A and Zhang T 1996 *Mater. Trans. JIM* **37** 185
[6] Peker A and Johnson W L 1993 *Appl. Phys. Lett.* **63** 2342
[7] He Y, Schwarz R B and Archuleta J I 1996 *Appl. Phys. Lett.* **69** 1861
[8] Drehman A J, Greer A L and Turnbull D 1982 *Appl. Phys. Lett.* **41** 716
[9] Ponnambalam V, Poon S J, Shiflet G J, Keppens V M, Taylor R and Petculescu G 2003 *Appl. Phys. Lett.* **83** 1131
[10] Lu Z P, Liu C T and Porter W D 2003 *Appl. Phys. Lett.* **83** 2581
[11] Wang X, Yoshii I, Inoue A, Kim Y H and Kim I B 1999 *Mater. Trans. JIM* **40** 1130
[12] Yi S, Park T G and Kim D H 2000 *J. Mater. Res.* **15** 2425
[13] Guo F Q, Wang H J, Poon S J and Shiflet G J 2005 *Appl. Phys. Lett.* **86** 091907
[14] Lin X H and Johnson W L 1995 *J. Appl. Phys.* **78** 6514
[15] Tang M B, Zhao D Q, Pan M X and Wang W H 2004 *Chin. Phys. Lett.* **21** 901
[16] Wu N C, Zuo L, Wang J Q and Ma E 2016 *Acta Mater.* **108** 143
[17] Xi X K, Wang R J, Zhao D Q, Pan M X and Wang W H 2004 *J. Non-Cryst. Solids* **344** 105
[18] Si J J, Wang T, Wu Y D, Cai Y H, Chen X H, Wang W Y, Liu Z K and Hui X D 2015 *Appl. Phys. Lett.* **106** 251905
[19] Huang H G, Ke H B, Wang Y M, Pu Z, Zhang P, Zhang P G and Liu T W 2016 *J. Alloys Compd.* **684** 75
[20] Zhang B, Pan M X, Zhao D Q and Wang W H 2004 *Appl. Phys. Lett.* **85** 61
[21] Zhang B, Zhao D Q, M X Pan, W H Wang and Greer A L 2005 *Phys. Rev. Lett.* **94** 205502
[22] Zhang B, Zhao D Q, Pan M X, Wang R J and Wang W H 2006 *Acta Mater.* **54** 3025
[23] Li S, Wang R J, Pan M X, Zhao D Q and Wang W H 2005 *Scr. Mater.* **53** 1489
[24] Jiang Q K, Zhang G Q, Chen LY, Wu J Z, Zhang H G and Jiang J Z 2006 *J. Alloys Compd.* **424** 183
[25] Li R, Pang S, Men H, Ma C and Zhang T 2006 *Scr. Mater.* **54** 1123
[26] Xi X K, Li S, Wang R J, Zhao D Q, Pan M X and Wang W H 2005 *J. Mater. Res.* **20** 2243
[27] Wu J, Wang Q, Chen F, Wang Y M, Qiang J B and Dong C 2007 *Intermetallics* **15** 652
[28] Li S, Wang R J, Pan M X, Zhao D Q and Wang W H 2008 *J. Non-Cryst. Solids* **354** 1080
[29] Yu H B, Yu P, Wang W H and Bai H Y 2008 *Appl. Phys. Lett.* **92** 141906
[30] Zhao Z F, Wen P, Wang R J, Zhao D Q, Pan M X and Wang W H 2006 *J. Mater. Res.* **21** 369
[31] Wang J Q, Wang W H and Bai H Y 2009 *Appl. Phys. Lett.* **94** 041910
[32] Ding D, Wang P, Guan Q, Tan M B and Xia L 2013 *Chin. Phys. Lett.* **30** 096104
[33] Wu C, Ding D and Xia L 2016 *Chin. Phys. Lett.* **33** 016102
[34] Kumar G, Tang H X and Schroers J 2009 *Nature* **457** 868
[35] Zhao K, Xia X X, Bai H Y, Zhao D Q and Wang W H 2011 *Appl. Phys. Lett.* **98** 141913
[36] Zhao K, Li J F, Zhao D Q, Pan M X and Wang W H 2009 *Scr. Mater.* **61** 1091
[37] Zhao K, Liu K S, Li J F, Wang W H and Jiang L 2009 *Scr. Mater.* **60** 225
[38] Jiao W, Zhao K, Xi X K, Zhao D Q, Pan M X and Wang W H 2010 *J. Non-Cryst. Solids* **356** 1867
[39] Zhang W, Guo H, Chen M W, Saotome Y, Qin C L and Inoue A 2009 *Scr. Mater.* **61** 744
[40] Xu B C, Xue R J and Zhang B 2013 *Intermetallics* **32** 1
[41] Xue, R J Zhao L Z, Zhang B, Bai H Y, Wang W H and Pan M X 2015 *Appl. Phys. Lett.* **107** 241902
[42] Singh D, Mandal R K, Srivastava O N and Tiwari R S 2015 *J. Non-Cryst. Solids* **427** 98
[43] Yadav T P, Singh D, Shahi R R, Shaz M A, Tiwari R S and Srivastava O N 2011 *Philos. Mag.* **91** 2474
[44] Fremy M A, Gignoux D, Schmitt D and Takeuchi A Y 1989 *J. Magn. Magn. Mater.* **82** 175
[45] Wang W H 2009 *Adv. Mater.* **21** 4524
[46] Cardarelli F 2000 *Materials Handbook* (London: Springer)
[47] Wang W H, Bian Z, Wen P, Zhang Y, Pan M X and Zhao D Q 2002 *Intermetallics* **10** 1249
[48] Lu Z P and Liu C T 2004 *J. Mater. Sci.* **39** 3965
[49] Liu C T and Lu Z P 2005 *Intermetallics* **13** 415
[50] Wang W H 2007 *Prog. Mater. Sci.* **52** 540
[51] Park E S, Chang H J, Kyeong J S and Kim D H 2008 *J. Mater. Res.* **23** 1995
[52] Chen N, Martin L, Luzguine-Luzgin D V and Inoue A 2010 *Materials* **3** 5320
[53] Miracle D B, Sanders W S and Senkov O N 2003 *Philos. Mag.* **83** 2409
[54] Yim H C, Busch R and Johnson W L 1998 *J. Appl. Phys.* **83** 7993
[55] Kissinger H E 1956 *J. Res. Natl. Bur. Stand.* **57** 217
[56] Zhang B, Wang R J, Zhao D Q, Pan M X and Wang W H 2004 *Phys. Rev. B* **70** 224208
[57] Böhmer R and Angell C A 1992 *Phys. Rev. B* **45** 10091
[58] Böhmer R, Ngai K L, Angell C A and Plazek D J 1993 *J. Chem. Phys.* **99** 4201
[59] Novikov V N and Sokolov A P 2006 *Phys. Rev. B* **74** 064203
[60] Wang W H 2012 *Prog. Mater. Sci.* **57** 487
[61] Wang W H 2006 *J. Appl. Phys.* **99** 093506