# Liquid Metal Based Stretchable Radiation-Shielding Film

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*We reported a stretchable and flexible radiation-shielding film based on room-temperature liquid metal. Conceptual experiments showed that the liquid metal based printing technology can achieve an ultrathin flexible radiation-shielding film with a thickness of 0.3 mm. Moreover, the yield strength and ultimate strength of the liquid metal film appear much better than those of a conventional lead-particle-containing radiation-shielding material. In order to evaluate the radiation-shielding performance of the liquid metal material, X-ray radiation experiments to compare the liquid metal film and conventional lead-particle-based shielding material under different stretching conditions were performed. The results indicate that the liquid metal shielding film could achieve a certain radiation-shielding performance. Furthermore, because of the screen-printing properties of liquid metal, a low-cost X-ray mask method using a liquid metal selective radiation-shielding film was also studied, which could serve as a highly efficient and practical method for the medical X-ray shielding applications or semiconductor lithography industry.*
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*Keywords: radiation shielding, stretchable X-ray shielding film, liquid metal, screen printing, X-ray lithography*

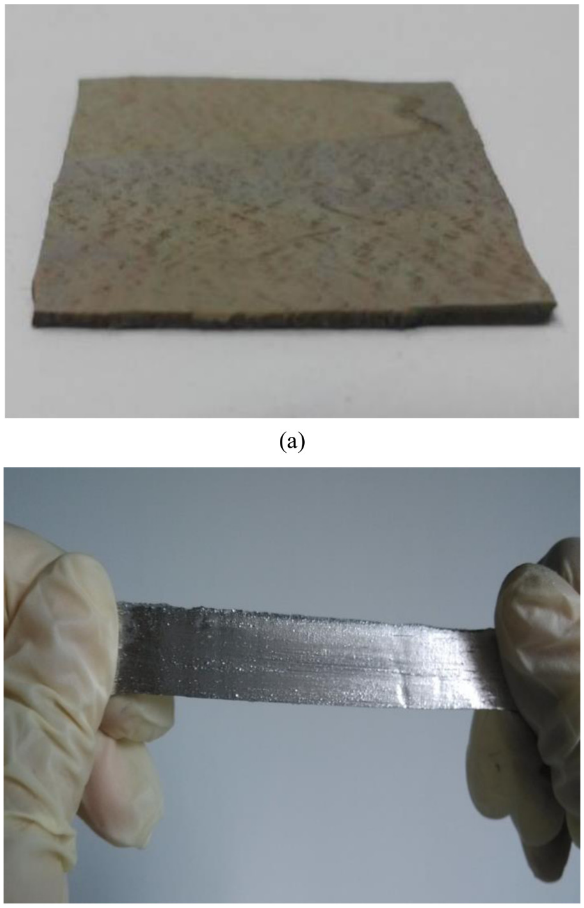
## 1 Introduction

Various types of radioactive rays have been extensively applied in the development of radioactive medicine and nuclear technology applications. Concurrently, the harmful effects of X-rays on the human body, e.g., skin burns, hair loss, leucopenia, and even myeloma, have gradually been recognized [1–4]. Hence, the research on radiation-shielding materials has become a significant and urgent subject. Currently, low energy X-ray shielding is usually made of lead glass or lead rubber. However, lead glass, which is a rigid material, is not suitable for flexible shielding applications. Although lead rubber possesses certain flexibility, due to the dispersed structures, a lead rubber shielding material is usually thick, with limited tensile deformation and a small ultimate tensile stress [5–7]. Therefore, the current flexible medical radiation shielding, including shielding gloves, shielding clothes, and local shielding, is inconvenient to use. Moreover, there is a risk of toxicity from the lead-containing materials [8–11].

Liquid metal printed electronics are a recent and original innovation in the field of flexible electronics [12,13]. A series of flexible electronic devices, e.g., liquid metal circuits, capacitors, sensors, and antennas, can be easily and conveniently produced using gas spray, screen printing, and even three-dimensional printing techniques [14–16]. This type of liquid metal, a gallium-based alloy with a melting point below 20 °C, is a liquid at room temperature, and has stable properties, an adjustable viscosity, and nontoxicity. Based on the natural metal properties and high viscosity of the liquid metal, we proposed here a flexible shielding film based on a liquid metal screen-printing technology. It has a very good shielding performance. Furthermore, it is nontoxic and has a smaller thickness and higher yield and ultimate strengths compared with conventional material. Thus, an excellent stretchable radiation-shielding material can be produced, which possesses outstanding practical value for flexible shielding gloves and shielding clothes, and can even be used for the medical X-ray shielding applications or X-ray lithography fields.

## 2 Materials and Methods

The current stretchable radiation-shielding material based on liquid metal can be quite thin, which is therefore highly flexible. Figure 1(*a*) illustrates the conventional lead rubber used in Shuang Ying PC14 radiation-shielding gloves, which have a thickness of 2 mm and the density of 1.6 g/cm$^3$. Figure 1(*b*) illustrates the liquid metal based stretchable radiation-shielding film, which has a


(a)

(b)

**Fig. 1 (*a*) Conventional lead-rubber flexible radiation-shielding material. (*b*) Liquid metal based ultrathin radiation-shielding material.**

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thickness of only 0.3 mm. The liquid metal is the alloy $Ga_{61}In_{25}Sn_{13}Zn_1$ (the subscript represents the mass ratio), which has a melting point of 8 °C and the density of 6.2 g/cm$^3$. Based on the screen printing process, the liquid metal was evenly coated on the silicon film. The smaller film thickness can produce a more comfortable experience for users, which is of great importance in the field of radiation-shielding clothes.

In order to comparatively evaluate the radiation-shielding performance of the liquid metal radiation-shielding material, 20 mm × 30 mm × 2 mm samples of both the lead rubber and liquid metal shielding film were employed in a radiation-shielding experiment. The liquid metal radiation-shielding material was fabricated by coating liquid metal onto a 2-mm-thick silicon film using a screen-printing method. Figure 2 shows the testing platform that was used to study the shielding performances of materials with different lengths: 30, 35, 40, 45, and 50 mm, respectively. A GE Optima X-ray machine was employed for the experiments, with an X-ray tube voltage of 55 kV and a tube current of 6.3 mAs.

## 3 Results and Discussion

**3.1 Mechanical Properties of Liquid Metal Stretchable Shielding Material.** One of the greatest advantages of the liquid metal radiation-shielding material lies in its high flexibility. Figure 3 illustrates the stretching elongation percentages of the traditional lead rubber and liquid metal shielding materials under different stretching forces, respectively. The materials for this experiment were 100 mm × 5 mm × 2 mm strips, and each material was stretched in the 100 mm direction. Figure 3 shows that when the stretching force is 12.5 N, the traditional lead rubber has obviously reached its yield limit. However, when the stretching force is 15 N, the liquid metal shielding material still has good flexibility and does not reach its yield limit. This is mainly because the even dispersion of lead particles in the conventional lead rubber weakens its tensile strength. In contrast, the liquid metal of the liquid metal radiation-shielding material is only coated on the rubber surface, which maintains the high flexibility of the rubber base.

The liquid metal radiation-shielding material possesses not only a higher yield strength but also a higher ultimate strength. Figure 4 shows a comparison of the tension limits of the lead-rubber shielding material and liquid metal shielding material (the material selection is the same as that of Fig. 3). It can be seen that the liquid metal radiation-shielding material possesses a higher tension limit. This is mainly because the lead particles contained in the lead-rubber shielding material lower the tensile strength of the rubber base. In contrast, the shielding metal of the liquid metal shielding material is mainly distributed on the flexible rubber surface, which does not affect the mechanical strength of the rubber, and thus allows a higher tension limit.

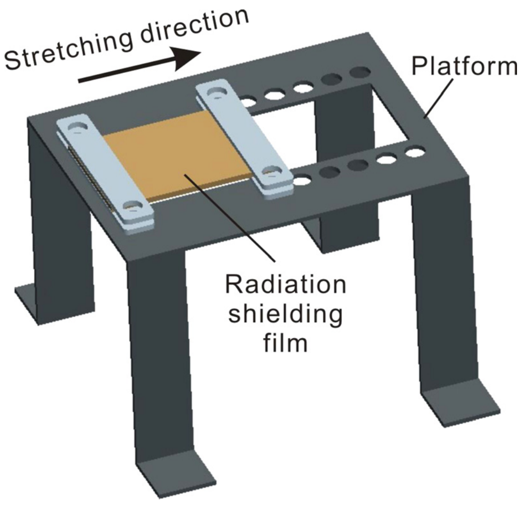


Fig. 2 Platform for radiation-shielding experiments

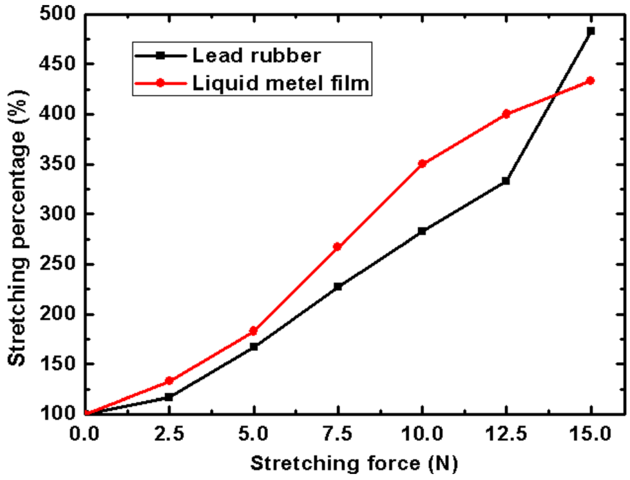


Fig. 3 Stretching elongation percentages of conventional lead rubber and liquid metal shielding material under different stretching forces

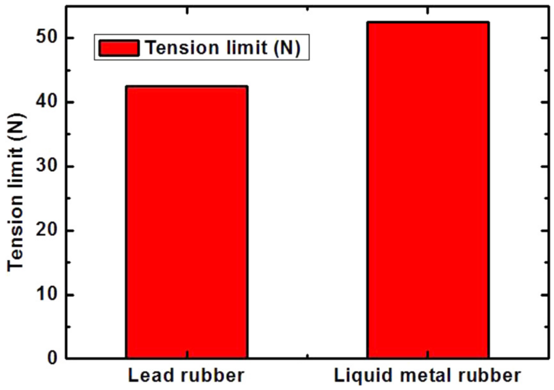
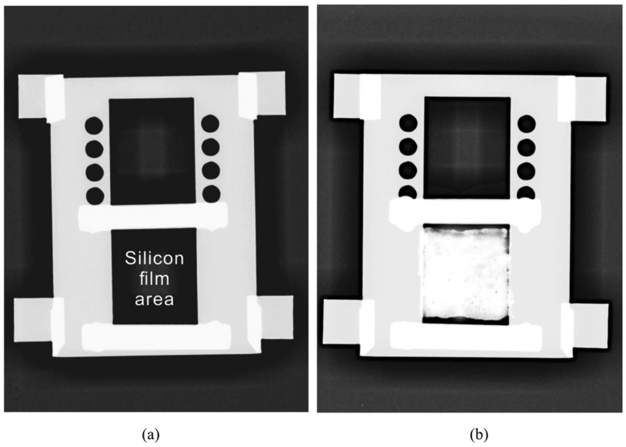


Fig. 4 Comparison of tension limits of lead-rubber and liquid metal shielding materials



(a)

(b)

Fig. 5 Comparison of X-ray photographs of silicon film (*a*) uncoated with liquid metal and (*b*) coated with liquid metal

**3.2 Radiation-Shielding Performance of Liquid Metal Stretchable Shielding Material.** Figures 5(*a*) and 5(*b*) show X-ray photographs of the silicon film uncoated and coated with the liquid metal, respectively. It can be seen from Fig. 5 that the uncoated silicon film can hardly block X-rays, whereas when it is coated with the liquid metal, it can obviously block X-rays. Since it was difficult to evenly coat it with liquid metal using a screen in the lab, and the liquid metal coating was thin, dark spots show up in Fig. 5(*b*), indicating a slightly inferior shielding effect.

Figure 6 shows the radiation-shielding abilities of the conventional lead-rubber and liquid metal shielding materials under different stretching conditions. The original length of 30 mm was stretched to lengths of 35, 40, 45, and 50 mm, respectively. In the radiation photograph data processing, the mean grayscale of the shielded area was employed as the evaluation criterion. In the case of complete shielding, the photograph was pure white, with a gray value of 255. Therefore, the radiation-shielding capability could be defined as $\eta = G/G_0$, where $G$ is the grayscale value of the shielded area, $G_0$ is 255 (complete shielding), and $\eta$ is the gray level.

It can be seen from Fig. 6 that the radiation-shielding ability gradually weakens with an increase in the stretching elongation for either material. This is mainly because the thickness of the shielding metal decreases with stretching. Hence, there is a stretching limit for the liquid metal radiation-shielding material. Once this stretching limit is reached, its radiation-shielding effect weakens. Furthermore, Fig. 6 shows that the performance of the current liquid metal radiation-shielding material cannot yet reach the performance of the conventional lead-particle-containing radiation-shielding material. This is mainly because the liquid metal coating is relatively thin. In addition, the current liquid metal material is mainly a gallium-based alloy, which has a radiation-shielding ability that is inferior to lead. From the practical aspect, the best solution is applying multilayer structure for liquid metal shielding film, which can effectively improve the radiation shielding capability, while retained the tensile strength of liquid metal shielding film. Besides, the greatest advantages of liquid metal shielding film lie in its high flexibility, biological safety, and higher adaptability, which is of great importance for applications to medical gloves, body coating, etc.

Generally, the attenuation of X-rays in a solid follows the simple exponential attenuation law. The linear attenuation coefficient of X-rays for a certain substance is related to the incident photon energy and shielding material atomic number. The total mass attenuation coefficient of the composite shielding material should be the summation of the mass attenuation coefficients of each element in the compound multiplied by its mass fraction in the shielding material. Thus, in the case of the liquid metal radiation-shielding film, the radiating shielding effect is mainly produced by the properties and thickness of the coated liquid metal. Although the lead particles in conventional lead rubber are evenly dispersed in the rubber, while the liquid metal in a liquid metal shielding material is coated on the surface of the rubber film, their radiation-shielding capabilities are both subject to the metal mass per unit area. Based on this theory, one can assume that multilayer liquid metal shielding film could offer much better shielding performance since the stacked liquid metal enhances the shielding capability.

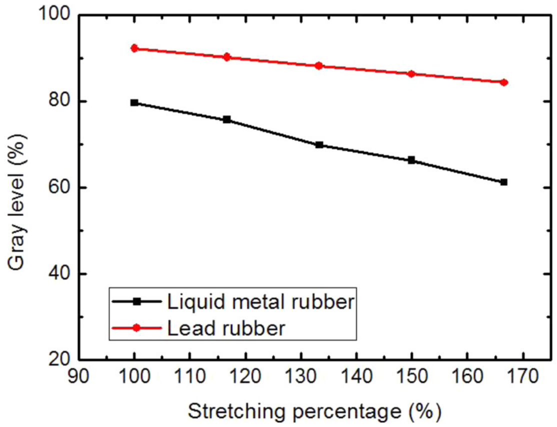
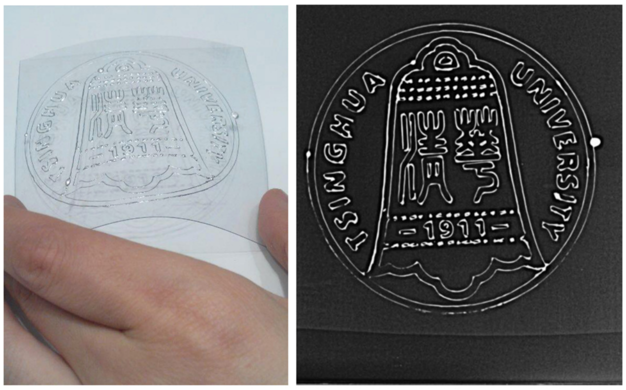


**Fig. 6 Comparison of radiation-shielding performances of lead-rubber and liquid metal materials under different stretching conditions**



(a) (b)

**Fig. 7 (*a*) Liquid metal based screen-printed selective X-ray shielding film and (*b*) related X-ray radiation photograph**

Liquid metal possesses an outstanding radiation-shielding ability. Because of its adjustable viscosity, selective surface printing can be conveniently achieved using some conventional approaches like cold spraying and screen printing. Hence, liquid metal can be used not only to produce full-shielding medical materials but also to efficiently produce a selective X-ray film using screen-printing technology. Figure 7 shows a selective X-ray shielding film fabricated using a liquid metal screen printing method, along with its X-ray radiation photograph. It can be seen that liquid metal can be conveniently printed onto any rigid or flexible base. The coated liquid metal can produce an outstanding radiation-shielding effect and high resolution. Therefore, the liquid metal selective radiation-shielding method can achieve an extremely low-cost and highly efficient X-ray lithography mask, which is of great value in the X-ray lithography field. Moreover, in medical applications, selective local shielding can also be rapidly achieved using a liquid metal printing, without molding. Thus, it will cost less.

## 4 Conclusions

In summary, a stretchable radiation-shielding film based on liquid metal was demonstrated and interpreted. Because of its excellent flexibility and good shielding capacity, liquid metal based radiation-shielding technology offers a promising solution for dealing with medical X-ray shielding applications. In addition, liquid metal based selective radiation shielding can be used to fabricate an extremely low-cost and highly efficient X-ray lithography mask. Overall, such a liquid metal based stretchable radiation-shielding film represents a feasible and cost-effective technology for the coming medical X-ray shielding applications.

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