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Toward an ideal electrical resistance strain gauge using a bare and single straight strand metallic glassy fiber†

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Electrical resistance strain gauges (SGs) are useful tools for experimental stress analysis and the strain sensing elements in many electromechanical transducers including load cells, pressure transducers, torque meters, accelerometers, force cells, displacement transducers and so forth. The commonly used commercial crystalline strain sensing materials of SGs are in the form of wire or foil of which performance and reliability is not good enough due to their low electrical resistivity and incapacity to get thin thickness. Smaller SGs with single straight strand strain sensing materials, which are called ideal SG, are highly desirable for more than seven decades since the first SG was invented. Here, we show the development of a type of minuscule length scale strain gauge by using a bare and single straight strand metallic glassy fiber (MGF) with high resistivity, much smaller lengthscale, high elastic limits (2.16%) and especially the super piezoresistance effect. We anticipate that our metallic glassy fiber strain gauge (MGFSG), which moves toward the ideal SGs, would have wide applications for electromechanical transducers and stress analysis and catalyze development of more micro-and nanoscale metallic glass applications.

metallic glassy fiber, strain gauge, strain sensing material, metallic glassy fiber strain gauge

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Although Thomson [1] in 1856 found that resistance of an electrical conductor changed when it was stretched, it was not until 1938 that the wire SG was invented by Simmons and Ruge independently [2]. The first commercial SG was fabricated by sandwiching a single strand of copper-nickel wire (with a diameter of 25 μm, a length of about 200 mm and a resistance of 120 Ω) between two layers of cigarette paper cemented with Durofix [2]. This kind SG was used almost entirely for static strain analysis. It was too long a time period to be applicable to analysis of strain with steep gradient and small transducers [3,4]. Then, Gall [5] worked out a method to draw out strain sensing wire into a grid and kept it at uniform tension while bonding it to an insulating backing material in 1944, but the failure rate of this kind of wire SG was high particularly on the rotor blade spars of helicopter. This drove Jackson [6,7] to develop foil SG in 1953. Nowadays, the foil SGs have almost completely superseded the original wire SGs. The lengthscale of SGs was shortened by the invention of wire and foil SGs. However, there are many problems with these SGs caused by the configurations of strain sensing materials, such as shear lag, heat dissipation, performance deterioration during installation caused by backing materials, unable to be installed on curved surface, and resistance change caused by the end loop and by transverse strain due to the thick dimensions of the strain sensing materials. Therefore, the ideal SG is highly desired for various engineering applications but has never been realized since the remarkable invention of foil SG [8], because no suitable strain sensing material with

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higher performance and processability was developed or discovered. Strain gauges using single straight strand strain sensing material with high resistivity, large elastic limit and thin thickness could avoid the above problems.

Metallic glasses with excellent mechanical and physical properties have promising applications in micro-electro-mechanical systems [9–12], while the high resistivity of the metallic glasses, which cannot be applied for either interconnects or electrodes [9], has to be considered. Recently, the micro and nanoscale metallic glassy fibers with high electric resistivity (about two to five times larger relative to commercial strain sensing materials) [13] and excellent mechanical properties have been developed [14]. Nearly perfect linear piezoresistance effect of MGFs was also investigated [15]. Furthermore, the high resistivity and small thickness of the MGFs are of paramount importance for substantially reducing the size of strain sensing element of SG [16], and the smoothness and uniformity of the MGFs make them reliable candidates for advanced strain sensing element of the SGs.

1 Experiment

$Pd_{40}Cu_{30}Ni_{10}P_{20}$ alloy ingot was prepared by induction melting a mixture of $Pd_{40}Cu_{30}Ni_{10}$ alloy ingot (which was prepared by arc melting pure Pd, Cu, and Ni) and pure P grains, and then was purified by fluxing technique using B_2O_3. And $Pd_{40}Cu_{30}Ni_{10}P_{20}$ metallic glassy rod was prepared by suction-casting method. $Pd_{40}Cu_{30}Ni_{10}P_{20}$ MGF with a diameter of about 6.5 μm was fabricated by drawing the metallic glassy rod via superplastic deformation in the supercooled liquid region. Details of preparing the MGF can be found in ref. [14].

The dependence of resistance on the applied strain of SGs was measured using a four-probe electrical resistance measurement method during tensile testing of the tensile specimen at room temperature. The constant-current of 0.1 mA through the MGFSG was provided by a KEITHLEY Model 2400 SourceMeter, and the voltage was measured by a KEITHLEY Model 182 Sensitive Digital Voltmeter. At the same time, the strain measurement was conducted on an Instron electromechanical 3384 test system by the extensometer at a strain rate of 2×10^{-4} s^{-1}. The stainless steel tensile specimen was prepared according to E8-04 ASTM standard.

A Philips XL30 scanning electron microscope (Eindhoven, the Netherlands) was deployed to image surface morphology of MGFSG and tensile specimen. Measurement of the temperature dependence of the gauge resistance of the MGFSG was carried out using a four-probe electrical resistance measurement method on a Physical Properties Measurement System (PPMS, Quantum Design Co. USA) with a heating rate of 3 K min^{-1} from 173 K to 373 K.

2 Morphology of MGFSG

The configuration of the MGFSG and the comparison with wire and foil SGs is shown in Figure 1. The MGFSG is simply a bare and single straight strand of $Pd_{40}Cu_{30}Ni_{10}P_{20}$ MGF (see Figure 1(b)) with fully glassy nature and micro-scale round cross-section which can be seen in refs. [14,15]. It is devoid of any backing material which is commonly necessary for the first generation of commercial strain gauge (illustrated in Figure 1(c)), wire (Figure 1(d)) and foil (Figure 1(e)) SGs as well as semiconductor strain gauges [16,17]. The resistivity of $Pd_{40}Cu_{30}Ni_{10}P_{20}$ MGF is 200 μΩ cm [15]. The MGF with a diameter of 6.5 μm was selected. In order to get a resistance of 120 Ω, which is the

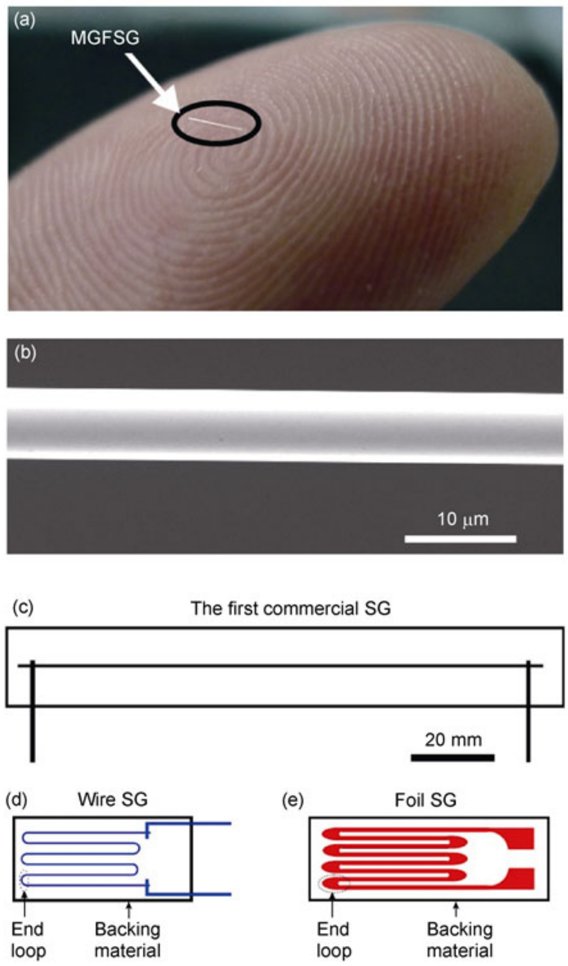

Figure 1 (Color online) Morphology of the MGFSG. (a) Optical image of the morphology of the glossy MGFSG with a diameter of about 6.5 μm and a length of about 2 mm. The MGFSG is a bare strain gauge without any backing materials. (b) SEM image of the surface morphology of the MGFSG. (c) The comparison of the size of the MGFSG and the first commercial wire SG with a single straight strand Copper-Nickel strain sensing material according to ref. [7]. The length of the MGFSG is only about 1% of that of the wire SG. (d) Schematic illustration of the morphology of wire SG with a grid of commercial strain sensing wire. (e) Schematic illustration of the morphology of foil SG.

most commonly used gauge resistance value, the length of the MGFSG cut from the MGF was about 2 mm. The length is substantially shorter than that of commercial strain sensing element of wire and foil SGs. For example, the wire SG with a single strand commercial strain sensing material with the same resistance is about 100 times longer than that of the MGFSG. The gauge length of the MGFSG is also about 2 mm which is comparable to the smallest foil SG [18], which is quite desirable for stress analysis [19] and size reduction of transducers [14]. The stiffness as well as the resistance to deformation of the MGFSG is much better compared with that of conventional SGs because of its small lengthscale [20]. The elasticlimit of MGF (~2%) is substantially larger than that of commercial strain sensing materials. For example, the $Pd_{40}Cu_{30}Ni_{10}P_{20}$ MGF (listed in Table 1) is about 2.2%. Commercial strain sensing materials without backing materials are easy to be damaged by plastic deformation because of their small elastic limit, while the MGFSG is much easier to be held and the backing materials for MGFSG is not necessary. Compared with the rough surface of commercial strain sensing elements of SGs [2], smoothness and uniformity of the MGFSG (see Figure 1(b)) guarantee its reliability. The MGFSGs have no end loop, and the problems caused by the end loop (such as shear lag, resistance change caused by the end loop) can then be totally excluded. The single straight strand MGF also benefits heat dissipation compared with grid strain sensing material of wire and foil SGs. The thin thickness of the MGF is beneficial to strain transmission (because of the higher ratio ($2/r$) [22] of surface to cross sectional areas) and reduction of resistance change caused by transverse strain [16]. In addition, because of superplasticity of metallic glasses in their supercooled liquid region, strain sensing elements of MGFSGs can be fabricated by one step [14]. While for the commercial strain sensing material, repeated drawing and annealing are necessary processes because of its limited plasticity [23].

3 Installation of MGFSG

Installation of the MGFSG is much easier compared with wire and foil SGs. Figures 2(a)–(c) schematically illustrate the installation of MGFSG on the stainless steel tensile specimen. An epoxy adhesive film with a thickness of about 20 μm was painted onto the surface of the tensile specimen (Figure 2(a)) to provide insulation between the MGFSG and the specimen, and the MGFSG was put onto the epoxy adhesive film along the loading direction. Four Pt electrodes were adhered onto the MGF by conductive silver adhesive (Figure 2(b)). The MGFSG was covered by another epoxy adhesive film (Figure 2(c)). Figure 2(d) shows the picture of the MGFSG adhered on the surface of the stainless steel tensile specimen which is prepared for testing the dependence of the relative change in resistance $\Delta R/R_0$ (where, $\Delta R=R-R_0$ is the change in resistance, and R_0 is the initial resistance) upon the applied strain ε of the MGFSG. Figure 2(e) is an enlarged picture of the installed MGFSG. We note that the eventual performances of the commercial SGs depended critically on the quality of the installation [24]. For the installation of MGFSG, the steps including mounting, clamping, and curing for wire and foil SGs [16] can be skipped, and the bare gauge ensures the most intimate adhesion of the gauge with the testing surface, similar to that of the semiconductor strain gauge [16]. Furthermore, the configuration of the MGFSG makes it easy to be installed onto testing materials. Unlike the foil SGs which must be installed on a flat plane, the MGFSG can be installed along a straight generatrix of curved surface. For example, it can be installed on the ridge of the tooth of the gear where it is impossible to install commercial strain gauge as shown in Figure 2(f). Applications of SG in strain analysis will be then much extended by using MGFSG.

4 Properties of the MGFSG

The measurement of the dependence of $\Delta R/R_0$ on ε of the $Pd_{40}Cu_{30}Ni_{10}P_{20}$ MGFSG is schematically illustrated in Figure 3(a). We chose a stainless steel tensile specimen with a smooth surface and homogeneous deformation in tension within 3% strain to ensure that the strain measured by the extensometer is equal to the strain of the SGs [25]. Figure 3(b) contrasts the dependence of $\Delta R/R_0$ on ε for the MGFSG and the foil SGs. The experimental data of the MGFSG were linearly fitted with a fixed intercept at 0. The adjusted R-square of the linear fitting of the dependence is 0.9999

Table 1 Gauge characteristics of MGFSG with a gauge resistance of 120 Ω and its commercial counterpart, where F, ε_e, K, $\Delta R_e/R_0$, L, and N are respectively gauge factor, elastic limit, temperature coefficient of resistance, relative change in resistance at elastic limit, gauge length, and strand number of strain sensing materials[a)]

SG	F	ε_e (%)	κ (10^{-5} K^{-1})	$\Delta R_e/R_0$ (%)	L (mm)	N
MGFSG	2.22(±0.16)	2.16(±0.08)	−10	4.95(±0.21)	2	1
foil SG	1.3–3.6	0.26–0.5	−11–600	0.4–1.8	1	~16

a) The gauge factor and the temperature coefficient of gauge resistance of foil SG were taken from ref. [17]. The elastic limit of foil SG was calculated from the data provided by ref. [21]. The relative change in resistance at the elastic limit of foil SG was calculated by multiplying gauge factor by elastic limit. The gauge length and the strand number of strain sensing material were taken from ref. [18].

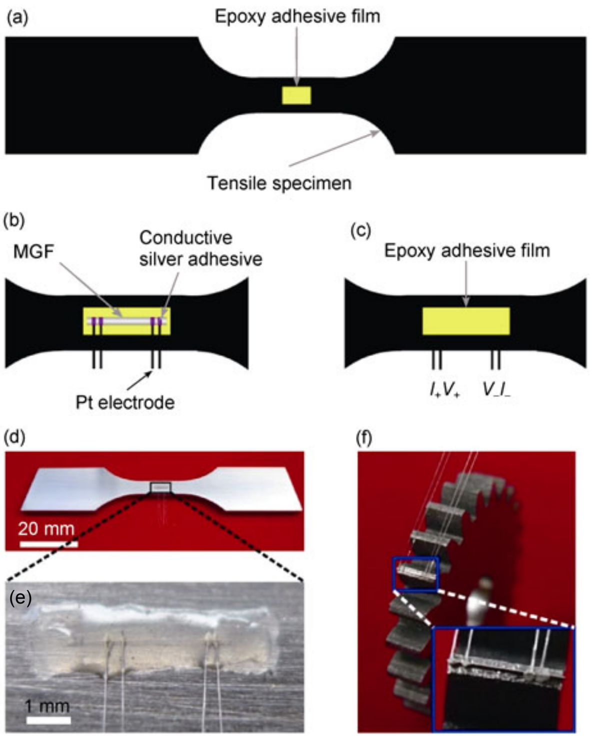

Figure 2 (Color online) Installation of the MGFSG for testing the dependence of the relative change in resistance on the applied strain. (a) A film of epoxy adhesive was painted on the surface of the stainless steel tensile specimen to provide electrical insulation between the strain sensing material and the tensile specimen. (b) The MGF was put onto the epoxy adhesive film along the loading direction. Four Pt electrodes were adhered onto the MGF by conductive silver adhesive for electrical resistance measurement. (c) The strain sensing material was covered by another film of epoxy adhesive. (d) MGFSG (which is indicated by the black rectangle) installed on the surface of tensile sample. (e) Morphology of the installed MGFSG. (f) MGFSG installed on the ridge of the tooth of a gear where a commercial strain gauge cannot be installed.

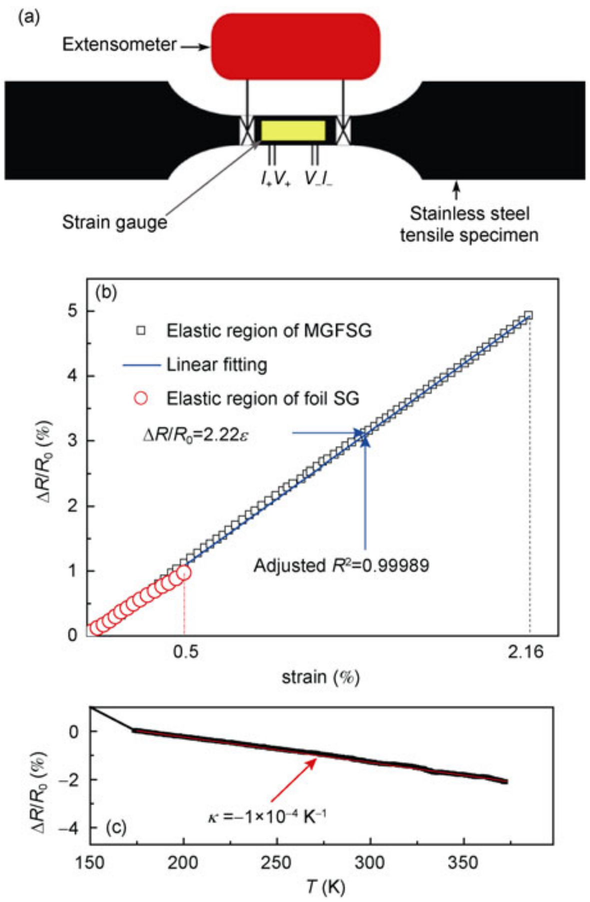

Figure 3 (Color online) Performance properties of the MGFSG. (a) Schematic illustration of the testing method of the dependence of $\Delta R/R_0$ on ε of SGs. (b) Plot of the dependence of $\Delta R/R_0$ on ε. Gauge factors are the slope of the linearity of linear fitting of the data points when the intercepts are fixed at 0. Gauge factor of the MGFSG is 2.22(±0.16). Elastic limits of MGFSG and foil SG are 2.16(±0.08)% and 0.5% respectively. (c) Temperature dependence of gauge resistance of MGFSG. The dependence is linear from 173 K to 373 K. Temperature coefficient (κ) of the gauge resistance is -1×10^{-4} K^{-1}.

and is as high as that of foil SG (0.9999). The result indicates that the dependence of $\Delta R/R_0$ on ε of the MGFSG is almost perfectly linear. The gauge factor (F) of the MGFSG, which is defined as the slope of the linear relationship between $\Delta R/R_0$ and ε (F=($\Delta R/R_0$)/ε) [3], is fitted to be 2.22 (±0.16). The value is comparable to that of commercial foil SGs as listed in Table 1. Geometric contribution of gauge factor is $1+2\nu$, where ν is Poisson's ratio of strain sensing materials. Because of the large Poisson's ratio (0.396) of $Pd_{40}Cu_{30}Ni_{10}P_{20}$ metallic glass [26], the resistivity contribution to the gauge factor of the MGFSG is relatively low. The nearly perfect linearity of the dependence of $\Delta R/R_0$ on ε of MGFSG is mainly due to large geometric contribution [4]. The strain limit of the MGFSG is 2.16 (±0.08) which is nearly the same as the elastic limit (2.2%) of $Pd_{40}Cu_{30}Ni_{10}P_{20}$ MGF, which is remarkably high compared with that of the foil SG (0.26%–0.5%) as listed in Table 1. In the strain limit, the MGFSG is elastic. Even though the strain limit of some kinds of foil SG is as high as 20%, it is plastic [16]. After plastic deformation, these SG cannot be repeatedly used. Therefore, as a strain sensing element of transducers, wire or foil SG can only work within its very narrow elastic limit. The measuring range of transducers using our MGFSG is enlarged by 4–8.5 times because the elastic limit of the MGFSG is 4–8.5 times larger than that of commercial foil SGs. The relative change in electrical resistance (so called piezoresistance effect [15]) at the elastic limit of our MGFSG is about 3–12 times higher than that of the commercial foil SG. In addition, temperature dependence of the gauge resistance is linear from 173 K to 373 K with a temperature dependent gauge resistance coefficient of -10×10^{-5} K^{-1}, which is much smaller than that of commercial foil SG (see Figure 3(c) and Table 1). Therefore, low temperature coefficient of resistance and the high corrosion resistance [11,12] of the MGFs make the MGFSG stable and with good temperature compensation. Furthermore, the gauge resistance of MGFSG at different temperatures can be easily calculated. For commercial strain sensing materials, their temperature dependence gauge resistance is nonlinear.

5 Conclusions

The advanced performance characteristics of the MGFSG in size and measurement limit compared with that of the conventional foil SGs are clearly illustrated. Our MGFSG has quadrupled elastic limit and is ten to one hundred times smaller in lengthscale compared with that of SGs with commercial strain sensing materials. Combining the nearly perfect linearity of the dependence of $\Delta R/R_0$ on ε, a relatively high gauge factor, high thermal stability and measurement reliability, high stiffness, and convenience for installation, the MGFSG is superior to that of the existing commercial SGs and close to ideal SGs. Our minuscule length scale MGFSGs are promising for a new generation of advanced strain gauge for stress analysis and strain sensing element of transducers.

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