Piezoresistance effect of metallic glassy fibers

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Smaller electrical resistance strain gauges (ERSG) are highly expected especially for micro-electro-mechanical systems while the reduction in the size of strain gauge is restricted by the relatively low resistivity and poor processability of conventional piezoresistive alloys. We investigate piezoresistive properties of a $Pd_{40}Cu_{30}Ni_{10}P_{20}$ metallic glassy fiber (MGF), and find that the resistivity, gage factor, elastic limit, and relative change in resistance of the MGF are superior to that of commercial crystalline ERSG piezoresistors. Combining with high flexibility, uniformity, smoothness, and nanoscale size in diameter, the MGFs are promising for submicroscale ERSGs.

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The piezoresistance effect describes the changing electrical resistance of an electrical resistor due to applied mechanical stress.[1] Piezoresistance effect is detected in most materials but the effect is particularly significant in some semiconductors[2,3] and crystalline alloys.[4,5] The applied strain affects resistivity, length, and cross-sectional area which determine the resistance of piezoresistors. In crystalline alloys the dominant effect for the piezoresistance effect is dimensional changes in length and cross-sectional area while in semiconductors the dominant effect is resistivity.[1–6] Up to now, little work on the piezoresistance effect in metallic glasses has been reported.[7] This is due to the low electrical resistance because of the relatively large cross-sectional area of the metallic glasses in ribbon or bulk form. The metallic glasses in bulk or ribbon form are then hard to be applied as the piezoresistors of electrical resistance strain gauge (ERSG).

The ERSGs are widely used as the transducer of stress analysis,[8] piezoresistive accelerometers, humidity sensors, deflection sensors, pressure sensors, and so on.[6] An ERSG, which is larger than the maximum strain region, will indicate a strain which is much lower than the actual strain. So far, the outside sheath dimension of the minimum ERSG is 1.1 $\times 2.2$ mm^2 (Ref. 9). Smaller ERSG are highly expected especially for micro-electro-mechanical systems in which the strain is measured by some complex system such as optical lever sensor in atomic force microscopy.[10] Due to the poor processability of commercial piezoresistor alloys, it is hard to produce piezoresistor with thickness of less than 20 μm.[4]

Micro- and nanoscale continuous metallic glassy fibers (MGFs) with high uniformity and smoothness were recently efficiently fabricated by drawing the metallic glassy rods via superplastic deformation in their supercooled liquid region.[11–14] The drawback of brittleness of metallic glasses can be mitigated in the MGFs.[14–17]

In this letter, the piezoresistive properties of a typical $Pd_{40}Cu_{30}Ni_{10}P_{20}$ MGF are investigated by four-probe electrical resistance measurement during tensile testing. It is found that the gage factor of the MGF is nearly the same as that of commercial copper–nickel and nickel–chrome alloys while the resistivity and relative resistance change upon the strain of the MGF is about two to four times larger than that of the commercial piezoresistors. The results indicate that the MGF is a potential piezoresistor of micro or submicroscale ERSG.

The preparation of the $Pd_{40}Cu_{30}Ni_{10}P_{20}$ MGF can be referred to as Ref. 14. The excellent smooth, uniformity, and high flexibility of the MGF with perfect circular cross-section is shown in Fig. 1. This eliminates unreliable results (Ref. 18) or even artifacts (Ref. 19) from the measurements caused by low uniformity, surface smoothness, and anomalous cross-section. The resistivity of the MGF at room temperature was measured by the four-probe electrical resistance measurement method. Figure 2 illustrates the piezoresistance effect testing assembly of the MGF. The MGF was adhered to a piece of paper with a rhombic hole at the center by the epoxy adhesive. Another paper holder was adhered to the former one. Four copper wire electrodes which were indicated by four red lines in Fig. 1(b) were adhered to the MGF by a conductive silver adhesive for detection of the resistance variation in the MGF during its tensile deformation. Tensile testing of the MGF was conducted on an Instron microtester 5848 with a strain rate of 1×10^{-4} s^{-1} and a

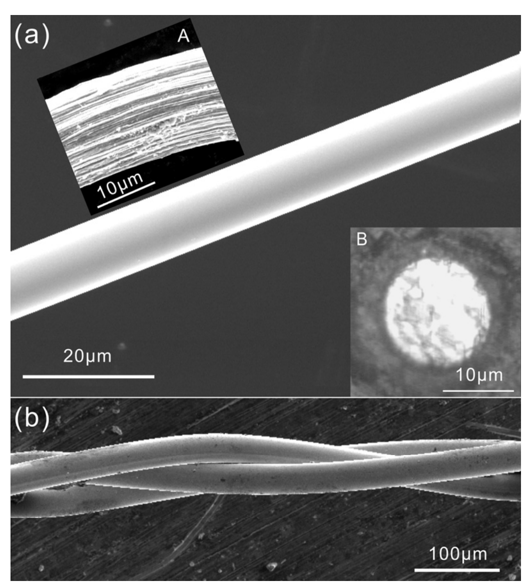

FIG. 1. (a) SEM image of the smooth and uniform $Pd_{40}Cu_{30}Ni_{20}P_{10}$ MGF. The inset A shows SEM image of morphology of crystalline alloy fiber, and the inset B is an optical image which shows the circular cross-section of the MGF. (b) SEM image of the microscale rope weaved from MGFs showing the excellent flexibility of the MGFs.

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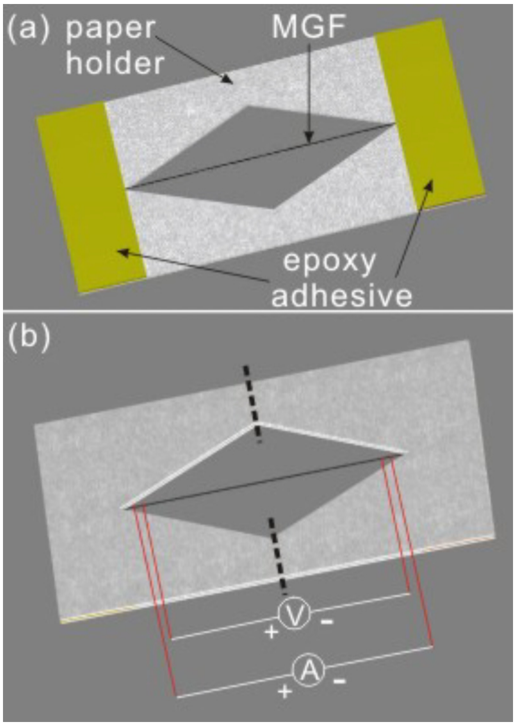

FIG. 2. (Color online) Schematic illustration of the piezoresistance effect testing assembly. (a) MGF was adhered to the paper holder with a rhombic hole at the center by epoxy adhesive. (b) The four copper wire electrodes were adhered to the MGF by conductive silver adhesive.

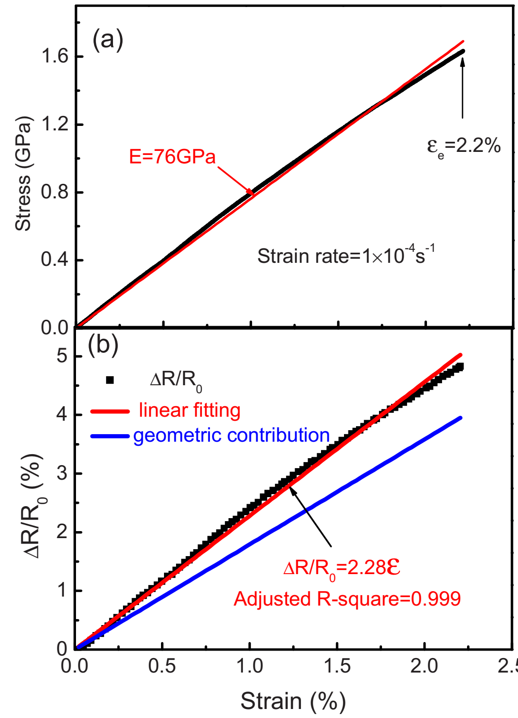

FIG. 3. (Color online) (a) Engineering stress-strain curve of $Pd_{40}Cu_{30}Ni_{10}P_{20}$ MGF. (b) Relationship between the relative change in resistance and strain of the MGF, which shows a nearly perfect linearity although the geometric contribution to the relative change in resistance is not dominant.

gauge dimensions of about $\phi 70$ μm$\times$20 mm. The gauge length was equal to the longer diagonal of the rhombic hole at the center of the paper holder. When the testing sample was fix on the cross-head, the paper holder was cutoff through the two dashed black lines as shown in Fig. 1(b). The tensile and resistance testing were conducted at the same time. The current of 1mA through the MGF was provided by a constant-current source, and the voltage was measured by a digital displaying panel of KEITHLEY 2000 Multimeter as shown in Fig. 2(b). The stress and strain were measured by the Instron microtester 5848.

The diameter of the MGF is 70 μm. The separation L and the voltage U between the inner two probes [see Fig. 2(b)] are 11.44 mm and 5.95 mV, respectively. The resistance is then $R=U/I=5.95\ \Omega$, where I is the constant current. And the resistivity ρ of the MGF calculated using $\rho=RA/L$ (A denotes the cross-sectional area of the MGF) is 200 $\mu\Omega$ cm, which is about two to five times larger than that of commercial piezoresistor materials as listed in Table I.

The engineering tensile stress-strain curve of the MGF is shown in Fig. 3(a). The Young's modulus E and elastic limit ε_e are determined to be 76 GPa and 2.2%, respectively. The electrical resistance is changed when the MGF was subjected to mechanical deformation, as shown in Fig. 3(b). The relative change in resistance $\Delta R/R_0$ (ΔR is the change in resistance at the elastic limit of MGF, R_0 is the initial resistance) at the elastic limit is 4.8%, which is two times larger than that of commercial constantan (see Table I). The sensitivity of piezoresistors depends on the ratio of $\Delta R/R$ to strain ε,[4,6] and the ratio is called the gage factor F: $F=[(\Delta R/R)/\varepsilon]$. We linearly fit the relationship between $\Delta R/R$ and ε, and the obtained gage factor of the MGF, which is the slope of the linearity, is ~2.3. The value is almost the same as that of the commercial piezoresistor materials listed in Table I.

The $\Delta R/R_0$ of piezoresistive materials is due to the change in resistivity or geometry induced by the applied mechanical stress (Ref. 6)

TABLE I. The comparison of the piezoresistance properties of typical crystalline alloys, metallic glass, and MGF.

Composition	$Ni_{68}Si_{15}B_{17}$ MG ribbon[a]	Constantan (wire)[b]	$Ni_{80}Cr_{20}$ [b,c]	Ni[b]	$Pd_{40}Cu_{30}Ni_{10}P_{20}$ MGF
$\rho(\mu\Omega$ cm)	152	45–52	100–110	⋯	200
K	2.0	2.1	2.1–2.3	−12	2.28
$(1+2\nu)$	⋯	1.66[d,e]	1.59[d,e]	1.62[e]	1.79[d]
P (%)	⋯	79	69–76	−13.5	78.5
E (GPa)	⋯	162	213[d,e]	⋯	76
ε_e (%)	⋯	1.1	⋯	⋯	2.2
R/R_0 (%)	4.6	2.4[b]	⋯	⋯	4.8

[a]Reference 7.
[b]Reference 4.
[c]The subscripts indicate weight percentage.Young's modulus and Poisson's ratio of crystalline metals were calculated from the way described in Ref. 23.
[d]Reference 23.
[e]Reference 24.

$$\frac{\Delta R}{R_0} = \frac{\Delta \rho}{\rho_0} + \frac{\Delta L}{L_0} - \frac{\Delta A}{A_0}, \tag{1}$$

where the $\Delta\rho$, ΔL, and ΔA are changes in resistivity, length, and cross-sectional area; and the ρ_0, L_0, and A_0 are primary resistivity, length, and cross-sectional area of MGF, respectively. The $\Delta\rho/\rho_0$ is resistivity contribution, and the $\Delta L/L_0 - \Delta A/A_0$ is the geometry contribution (G) of the MGF to the changes in resistance. The $\Delta R/R_0$ of semiconductors is primarily due to resistivity contribution while for the crystalline alloys the dominant contribution is from geometry terms.[1–6] The relationship between geometric contribution G and Poisson's ratio ν, and strain ε can be expressed as (Ref. 6)

$$G = (1+2\nu)\varepsilon. \tag{2}$$

The fraction of the geometry contribution in $\Delta R/R_0$ is

$$P = \frac{G}{\Delta R/R} = \frac{(1+2\nu)\varepsilon}{F\varepsilon} = \frac{1+2\nu}{F}. \tag{3}$$

Usually, the bigger the P value, the better the linearity of the relationship between the $\Delta R/R_0$ and ε (Ref. 4). For some materials, such as Ni (see Table I) which has an attractively high sensitivity, is actually highly nonlinear because of low P value (−13.5%). This means that the sensitivity varies with strain and induces unreliable for strain gauge piezoresistors.

For $Pd_{40}Cu_{30}Ni_{10}P_{20}$ metallic glass, its Poisson's ratio is 0.396 (Ref. 18). At its elastic limit, the relative change in resistance and geometry are 4.8% and 3.9%, respectively. The P value of the MGF is then determined to be ~79%, which reaches the largest value of the commercial materials (69%–79%). The resistivity contribution of the MGF is $1-G=21.5\%$ which is about an order of magnitude lower than that of semiconductors.[2,3] The relationship between $\Delta R/R_0$ and ε of the MGF is plotted in Fig. 3(b). It can be seen that the relationship between the $\Delta R/R_0$ and strain shows excellent linearity (the adjusted R-square of the linear fitting that is 0.999) as shown in Fig. 3(b). The results indicate that the MGF has the excellent accuracy and repeatability as the piezoresistors of strain gauges.

The properties of uniformity and smoothness of $Pd_{40}Cu_{30}Ni_{10}P_{20}$ MGF make it be reliable and repeatable piezoresistor. The much lower Young's modulus of the MGF comparing with that of the commercial piezoresistive materials leads to the excellent flexibility of the MGF,[14,20] which makes the MGF much easier to be installed to the backing materials. In addition, the elastic limit of the MGF is about two times larger than that of the commercial piezoresistive materials. That means that the strain limit of the MGF strain gauge could be doubled. The gauge resistance typically range from 120–350 Ω[4]. The piezoresistor of the commercial ERSG is usually a grid of piezoresistive wire. This is due to the low resistivity of the commercial piezoresistive material, which is difficult to produce the smooth and uniform piezoresistive wire with thin diameter by using these materials. More lines in the grid will lower the gauge factor, because there are shear lag at the end of the grid. Due to high resistance and the nanoscale diameter of the MGF, the total length of the piezoresistor with resistance of 120 Ω can be reduced to 260 nm when the MGF with diameter of 74 nm (Ref. 14) be used for the piezoresistor. The ratio of length to diameter of the MGF is less than four. Therefore, in principle, the single nanofiber can be used as the piezoresistor, and the drawn back brought by the grid end, such as shear lag and transverse strain, can be eliminated completely. The gauge length of 260 nm is much smaller than that of the smallest commercial ERSG length (so far is about 0.2 mm).[9] The strain limit of the MGF piezoresistor would be two times smaller than that of commercial piezoresistor because of the two times larger elastic limit of the MGF. Furthermore, the good corrosion resistance (Ref. 21) and low temperature coefficient of resistance (Ref. 22) of the MGFs make the piezoresistive material stable and good temperature compensation.

In conclusions, the $Pd_{40}Cu_{30}Ni_{10}P_{20}$ MGF has a sensitive piezoresistive response showing perfect linearity with tensile strain. The uniformity and smoothness of the MGFs are potential excellent piezoresistor of the ERSG with high measuremental reliability. The high flexibility of the MGF makes them easily to be installed onto backing materials. And the high elastic limit of the MGF could double the strain limit of the MGF piezoresistor. The high resistivity and nano to microscale size of the MGF make it a potential piezoresistor of submicroscale ERSGs which are highly expected for microelectro-mechanical systems.

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