Preparation Technology of Stretchable Electrode Based on Laser Cutting

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Abstract: Wearable electronics have shown their profound impact in military, sports, medical and other fields, but their large-scale applications are still limited due to high manufacturing costs. As an advanced micro-fabrication process, laser processing technology has the advantages of high speed, high flexibility, strong controllability, environmental protection and non-contact in preparing micro-nano structures of wearable electronics. In this paper, a 355 nm ultraviolet laser was used to pattern the copper foil pasted on the flexible substrate, and the interconnection electrodes and wires were constructed. A processing method of multi-parallel line laser cutting and high-speed laser scanning is proposed to separate and assist in peeling off excess copper foil. The process parameters are optimized. A stretchable 3 × 3 light-emitting diode (LED) array was prepared and its performance was tested. The results showed that the LED array can work normally under the conditions of folding, bending and stretching, and the stretch rate can reach more than 50%. A stretchable temperature measurement circuit that can be attached to a curved surface was further fabricated, which proves the feasibility of this process in the fabrication of small-scale flexible wearable electronic devices. Requiring no wet etching or masking process, the proposed process is an efficient, simple and low-cost method for the fabrication of stretchable circuits.

Keywords: wearable electronics; laser cutting; stretchable electrodes; interconnect structure

1. Introduction

Compared with traditional equipment, stretchable electronic products have the advantages of lightness, robustness and flexibility, and are widely used in medical and health care, consumer electronics, energy, national defense equipment and other fields [1,2]. One of the key technologies for the preparation of stretchable circuits is the preparation of stretchable electrodes (or wires). Currently, the main methods for preparing stretchable electrodes are as follows: The first method is based on the change of electrode patterns to withstand tensile strain, usually in the shape of wave, spiral and snake; the second is to add special conductive nanomaterials, such as graphene, carbon nanotubes, liquid metals, metal nanowires and conductive polymers, into the elastic polymer matrix [3,4].

Du et al. [5] transferred molybdenum pentachloride-sandwiched bilayer graphene prepared in a closed environment to an elastomer substrate, which was used as an epidermal electrode for health monitoring. Wiranata et al. [6] used an automatic brush machine to draw carbon nanotube powders on elastomers to prepare carbon nanotube powder-based stretchable sensors, and demonstrated the system integration of stretchable sensors by embedding the stretchable sensors in cotton gloves. Guo et al. [7] poured the gallium indium tin alloy liquid metal at room temperature into the elastic silicone tube, which can withstand the stretching, torsion and bending of large deformation, and has good...
electrical contact stability with the external circuit. Magnetic energy harvester for flexible liquid metal coils collects magnetic field energy generated by alternating current wires. Huang et al. [8] prepared thin-film electrodes by doping redox-reactive manganese dioxide and high-conductivity silver nanowires into activated carbon-based materials, which effectively improved the conductivity of thin-film electrodes. Li et al. [9] proposed an ionic conductor polymer based on polyacrylic acid (PAAc) and deep eutectic solvent (DES), and the resulting PAAc-DES gel had good tensile properties, high adhesion, and good anti-drying and anti-freezing properties, it can be used as a skin electrode to record surface EMG signals with high signal quality. Reference [10] proposed a preparation scheme combining two-dimensional graphene layer, silver nanowires and PEDOT:PSS, and the hybrid electrode developed overcomes the limitations of commonly used metal nanowires and ionic conductor electrodes in the application of AC electroluminescence.

In the above methods, there are some disadvantages, such as that the gel electrode is easy to volatilize, has poor conductivity and unstable conductivity, silver nanowires and liquid metal materials are expensive, and the preparation of carbon material electrodes requires complex technological processes and high-end operating equipment. The development of a simple and low-cost way to fabricate stretchable electronic devices is a current research hotspot. Laser processing technology has the advantages of high processing efficiency, strong controllability and non-contact processing, and can be used for micro-nano processing [11–13]. In this paper, a stretchable substrate is prepared by spin coating and attached with copper foil, and the copper foil is cut by ultraviolet laser processing technology. Then, the excess copper foil on the substrate is removed by laser scanning-assisted peeling, and electronic components are installed. Finally, the stretchable circuit was obtained by encapsulation and curing, and a simple and convenient fabrication process of the stretchable circuit was optimized and summarized.

2. Materials and Methods

When the ultraviolet laser beam irradiates on the metal surface, the metal will melt, vaporize and evaporate [14,15]. Using this effect, electrode patterns can be drawn directly on metal films. As shown in Figure 1, Bastien et al. [16] developed an innovative mode based on the combination of laser ablation and heat release band, and successfully packaged and manufactured a highly stretchable metal electrode in PDMS. The 50 µm thick aluminum foil was first attached to the glass slide with heat release tape. Then, the laser ablation patterned aluminum foil was used to create the interconnected metal structure. The excess aluminum foil was then removed and the packaging was completed. With a maximum resistance increase of only 1% at 60% tensile test conditions, this ultra-low resistance interconnect electrode can meet the general application of weak current engineering.

![Figure 1. Process of laser cutting metal foil to prepare stretchable electrode.](image)

The stretchable circuit in this paper includes three parts: electronic components, stretchable interconnect electrodes and flexible encapsulation layers. In order to improve the reliability of the circuit during the stretching process, it is necessary to ensure that there is a good connection between the various parts of the circuit during the stretching process.
The stretchable electrodes were prepared according to the process shown in Figure 2. First, the stretchable substrate constructed by Ecoflex was spin-coated on the glass slide, then Polyimide (PI) was spin-coated on the stretchable substrate, and a layer of copper foil was attached, and then the copper foil is patterned by laser etching, using a laser-assisted method to warp the edges of the excess copper foil, and finally the excess copper foil is stripped off with a tool, and the target electrode is left on the surface of the Ecoflex substrate.

![Figure 2. Stretchable electrode preparation process. (a) Fabrication of stretchable circuits; (b) laser cutting path; (c) laser irradiation causes the edges of the excess electrodes to deform to facilitate peeling; (d) target electrode is preserved.](image)

3. Preparation of Stretchable Circuit

The preparation process is mainly divided into three parts: the preparation of stretchable substrate, the preparation of the electrode by laser patterning and the assembly and packaging of circuit. In order to prepare the stretchable electrode with better performance, it is necessary to evaluate the influence of the main parameters of laser processing equipment on the notch quality of copper foil, so as to optimize the processing parameters.

3.1. Optimal Design of Stretchable Electrodes and Simulation of Tensile Properties

A variety of typical electrode interconnection structures are studied by establishing a simulation model, and the optimal structure type and size parameters are determined. First, metal copper was selected as the electrode material, and the typical stretchable interconnect structures (U-shaped, V-shaped, horseshoe-shaped) were designed and simulated, respectively. Secondly, according to the actual situation of laser processing and raw material parameters, the size parameters are set, and further optimization through simulation is used for the design of laser processing interconnect electrode patterns. As shown in Figure 3a, the single-cycle models of the three stretchable interconnect structures were established using Workbench.

The key factors that lead to tearing or failure of an electrode when it is stretched are its stress and plastic strain. Figure 3b shows the variation of the maximum equivalent stress and maximum equivalent plastic strain with the tensile rate of the three electrodes under the same tensile conditions. It can be seen that when the stretching rate gradually increases, the maximum equivalent stress and the maximum equivalent plastic strain of the three electrodes increase with the increase of the electrode stretching rate: the maximum equivalent stress of the V-shaped electrode changes the most, from 320.5 MPa increased to 562.1 MPa; followed by U-shaped electrode, the maximum equivalent stress increased from 315.4 to 406.5 MPa; the maximum equivalent stress of the horseshoe-shaped electrode was always the smallest, increased from 299.4 to 392.9 MPa. As shown in Figure 3c, for the maximum equivalent plastic strain, the horseshoe electrode still performs optimally, increasing from 0.4% to 9.3%. Therefore, during the stretching process, the maximum equivalent stress and equivalent plastic deformation of the interconnected electrodes with the horseshoe shape in the three structures are always kept the minimum, and there is the...
possibility of bearing a larger tensile load. According to the above analysis, a stretchable circuit was fabricated using electrodes with a horseshoe-shaped structure.

**Figure 3.** Finite element simulation of 3 types of interconnected electrode. (a) The 3 types of interconnecting electrodes; (b) relationship between maximum equivalent stress and tensile rate; (c) relationship between maximum equivalent plastic strain and tensile rate.

### 3.2. Preparation of Stretchable Substrates

The substrate is an important part of the stretchable circuit, carrying the electrodes and components. Pour equal proportions of Ecoflex 00-30 (smooth-on, USA) A and B into a beaker and stir well. Seal with clingfilm and refrigerate at −18 °C for 1 h to remove small bubbles from the gel. Glass plate was selected as the bearing substrate of the base layer, and the glass plate was cleaned by JP-020S (Skymen, China) ultrasonic cleaning machine with anhydrous ethanol for 15 min, and then dried. The Ecoflex mixture is rotated by a leveling machine and cured.

Since the laser is very sensitive to changes in the focal length during processing, once the surface of the sample is undulating, the processing effect will be unsatisfactory. In order to obtain a good processing effect, a flat and uniform elastic film is required as a substrate to fabricate a circuit first. For the preparation of thin films, the spin coating method can accurately control the thickness and uniformity of the thin films, and is easy to operate and cost-effective. The elastic base film has uniform texture, good performance and can be used as a substrate was prepared by a gluer. The experiment used the EZ6-S (Jiangsu Lebo, China) smart gluer. The principle is to adsorb the hard substrate through a hollow turntable. Thereby, negative pressure is generated, the hard substrate to be spin-coated is adsorbed on the turntable, and then the coating material mixed glue is dropped on the surface of the hard substrate, and the rotational speed of the turntable is controlled by adjusting the motor speed, thereby changing the centrifugal force and the desired film thickness. The working schematic of the glue dispenser is shown in Figure 4a. After spin coating, the colloid is cured and peeled off from the hard substrate to obtain an elastic film.

In the experiment to explore the effect of spin coating speed on substrate thickness, the amount of glue dispensed, the acceleration and the duration of the uniform spin coating stage were used as quantification, and the total spin coating time varied with the target spin coating speed. As shown in Figure 4b, the film thickness decreases with increasing spin coating speed, and the amount of film thickness variation decreases with increasing speed. When the spin coating speed reaches a certain value, the thickness of the film will no longer change. The films had similar thicknesses when the spin coating speed reached 1600 rpm in the experiments and the spin coating speed was continued to increase.
Figure 4. Spin Coating Flexible Substrates. (a) Schematic diagram of spin coating; (b) relationship between film thickness and spin coating speed; (c) relationship between film thickness and spin coating time; (d) relationship between film thickness and spin coating time initial glue drop.

As shown in Figure 4c, in the experiment to explore the effect of spin coating time on the thickness of the substrate, the acceleration was uniformly set to 600 rpm/s, the initial dispensing amount was 0.5 mL each time, and the spin coating speed was 1200 rpm. The film thickness decreased from 132 to 69 µm when the spin coating speed was constant and the spin coating time was increased from 13 to 53 s. With the increase of spin coating time, the film thickness will not change in the end, this is because under sufficient spin coating time, the colloid on the hard substrate is fully spin-coated and reaches a relatively balanced state, continue to increase the spin coating time to balance. The state is not broken and the film thickness is not affected.

The small amount of glue and the setting of equipment parameters before spin coating sometimes make the glue unable to cover the entire substrate. When exploring the effect of the initial amount of colloid on the final film thickness, it is necessary to ensure that the amount of glue dispensed in each experiment must be such that the mixed colloid can completely cover the surface of the hard substrate. Figure 4d shows the effect of the initial dispensing amount on the film thickness. When the minimum dispensing amount is 0.5 mL, the end of spin coating can completely cover the hard substrate. When the dispensing amount increases from 0.5 to 2.5 mL, the film thickness has no obvious difference. It shows that the colloid that can stay on the surface of the substrate and form a thin film after spin coating is fixed under a certain spin coating speed and time. At the same time, according to the experimental results of the two control groups, in the case of no spin coating, dripping 0.5 and 1 mL of colloid on the hard substrate has the same film thickness after curing. In summary, both the spin coating speed and the spin coating time have an effect on the film thickness, and the effect of the spin coating speed is greater than that of the spin coating time. The initial amount of glue drop has no obvious effect on the film thickness, but adding more mixed colloids will cause a great waste of raw materials.
3.3. Performance Evaluation of Laser Patterned Copper Foil

The surface of Ecoflex is further coated with a layer of PI solution, which makes the copper foil and substrate adhere well [17,18]. When it is semi-dry, paste the copper foil (red copper) and fully roll it with a pressing roller, so that the copper foil can be spread out better. The copper foil is directly patterned by low-power ultraviolet laser to realize the processing of the extendable interconnect electrode. The processing equipment is HG-LU-5 (Wuhan Huagong, China) ultraviolet laser marking machine. The main parameters are shown in Table 1. AutoCAD software was used to draw the vector graph of electrode contour, and Ezcad software was used to mark the graph and control the cutting of copper foil.

Table 1. Main parameters of the laser.

<table>
<thead>
<tr>
<th>Laser Specification and Model</th>
<th>Huaray DPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum power</td>
<td>5 W</td>
</tr>
<tr>
<td>laser wavelength</td>
<td>355 nm</td>
</tr>
<tr>
<td>spot size</td>
<td>20 μm</td>
</tr>
<tr>
<td>resolving power</td>
<td>1 μm</td>
</tr>
<tr>
<td>repetition accuracy</td>
<td>3 μm</td>
</tr>
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</table>

The processing effect of laser varies greatly under different processing parameters, so it is necessary to optimize the processing parameters to obtain better processing effect. In general, the laser marking machine needs to adjust the parameters of laser processing speed, pulse repetition frequency and processing times [19–21]. Among them, the processing speed refers to the distance of movement per unit time; pulse repetition rate is the number of pulses released by laser per second; the number of processing is the number of repeated laser scanning for the processing path. A copper foil 40 μm thick was selected to process a straight line 10 mm long. The fixed processing times were 10 times. The control variable method was used to conduct experiments to study the effects of pulse repetition frequency and laser cutting speed on the notch quality one by one.

1. Pulse repetition frequency

In this experiment, the pulse repetition frequency range of ultraviolet laser marking machine was 0–100 KHz. In order to explore the influence of laser pulse repetition frequency on cutting, experimental parameters were set as follows: the cutting speed was 150 mm/s, the pulse repetition frequency was set as 20, 40, 60, 80 and 100 KHz respectively, and the processing times were 10 times. The measurement results of incisions at different pulse repetition frequencies are shown in Figure 5a. It can be seen that there are black oxidized parts on both sides of the laser cut, which is caused by the thermal effect of laser cutting. In laser cutting, the processing area is the highest temperature, due to the thermal conductivity of the metal in the vicinity of the incision and the accumulation of higher heat, so the copper is under high temperature in the air oxidation phenomenon.

![Figure 5](image_url)

Figure 5. (a) Slitting at different pulse repetition rates. (b) Slit cutting at different cutting speeds.
With the increase of frequency, the thermal effect decreases, and there is a nonlinear inverse relationship between pulse repetition frequency and slit width. The pulse repetition frequency increases from 20 to 100 KHz, and the slit width decreases from 32 to 15 µm. When the frequency reaches a certain value, the slit width changes very little. With the increase of laser pulse repetition frequency, the flatness of the incision becomes worse, while the width of the incision and the width of the heat affected zone decrease, which is caused by the influence of pulse repetition frequency on the peak power of the laser. When selecting the pulse repetition frequency, it is necessary to reduce the influence of thermal effect as much as possible under the premise of ensuring the laser cutting effect.

2. Laser cutting speed

Laser cutting speed is also one of the important factors affecting the effect of laser cutting, directly affecting the width of the incision and surface roughness. In this experiment, the cutting speed of laser marking machine ranges from 0 to 7000 mm/s. Due to the low absorption rate of ultraviolet laser on copper foil, the action time between laser and copper foil is shortened due to the excessive cutting speed, so the efficiency of high-speed processing is low. In order to explore the impact of laser cutting speed on notch quality, pulse repetition frequency of 80 KHz was selected for the test. Figure 5b shows the notch of copper foil under low-speed laser cutting. When the cutting speed increases from 50 to 250 mm/s, the cut width decreases from 25 to 20 µm. Laser cutting speed has little effect on the slit width. When the cutting speed is slow, the action time of laser energy in the incision will be prolonged, and the effective spot area and slit width will increase.

At the cutting speed of 50 mm/s, a large amount of material accumulation was observed on both sides of the incision, which was caused by excessive ablation due to the slow cutting speed, which made the incision larger and the edge rough. Therefore, on the premise of ensuring that the cutting through, choose a larger cutting speed as far as possible. In addition, when the cutting speed is greater than 1000 mm/s, the energy obtained per unit area of the workpiece surface is reduced, and the situation cannot be cut through. Only when the processing times are increased to more than 40 times, can the obvious incision be seen, but this will undoubtedly greatly reduce the processing efficiency. When the cutting speed is further increased to 5000 mm/s, the laser cannot completely cut through the copper foil, and a series of continuous circular holes with the diameter of about 15 µm are generated on the copper foil. The spacing of adjacent holes increases with the increase of cutting speed.

To sum up, for the laser cutting of copper foil, the quality of the incision is inseparable from the laser energy. When the input energy is large, it is easy to obtain a wider incision, accompanied by a more serious thermal effect. When the cutting speed increases, the oxidized area on both sides of the cut decreases significantly. Increasing the cutting speed can reduce the oxidation on the metal surface to a certain extent. When the cutting speed is too fast, the width of the cut is reduced accordingly. At this time, it is difficult to cut through the copper foil simply by increasing the processing times, but it is easy to cause the accumulation of heat on the surface of the material to cause serious deformation of the copper foil. At the same time, when the laser processing speed is too large and the processing distance is limited, the laser speed change needs to be carried out in a very short time, which makes the stability of the processing decline, and even cannot cut through the copper foil.

Therefore, when choosing to cut copper foil, it is necessary to ensure that low-speed cutting is preferred on the premise of being able to cut through copper foil, so as to improve the cutting efficiency and obtain better processing quality. Through many comparative experiments, the ideal processing parameters of copper foil were determined as follows: cutting speed 150 mm/s, processing frequency 80 KHz, processing times 10 times.
3.4. Preparation of Electrode

3.4.1. Multi-Parallel Line Laser Cutting

When separating the target electrode from the excess copper foil, contact or pull between the target electrode and the excess copper foil should be avoided to prevent the target electrode from shifting or being detached from the substrate. As shown in Figure 6a, the cut morphology of copper foil was observed by super depth-of-field microscope DSX510 (Olympus, Japan), and Figure 6b was the cut section. As the upper surface of copper foil receives more energy during laser cutting, the width of the upper surface of the cut is larger than that of the lower surface, and the cut section is approximately trapezoidal. At the same time, a small amount of molten metal material accumulated on both sides of the incision surface, affecting the stripping.

![Figure 6a](image)

**Figure 6a.** Slit topography.

![Figure 6b](image)

**Figure 6b.** Slit profile.

![Figure 6c](image)

**Figure 6c.** Slit profile model diagram.

Figure 6c is the incision profile model diagram. In practical analysis, because the thickness of copper foil is very small, the slope of the cut is ignored and the section is approximately rectangular. In order to successfully separate the target electrode from the excess copper foil, the excess copper foil to be stripped must be kept a sufficient distance from the target electrode, which should satisfy the following relationship:

$$
\begin{align*}
    d &> h \\
    d &\geq \frac{\sqrt{L^2+L^2}-L}{2}
\end{align*}
$$

(1)

where, $d$ is the width of the bottom of the incision, $h$ is the thickness of the copper foil, and $L$ is the line width of the target electrode.

Among them, $d$ can be changed by changing the laser cutting method. In this paper, a multi-parallel cutting method is selected to widen the incision, that is, two or more parallel lines with the same spacing are used to outline the contour of the target electrode. This method can effectively expand the range of laser ablation zone and increase the cutting line width, and the parallel line should be derived in the direction of excess copper foil, otherwise the final electrode width will be reduced, affecting the mechanical and electrical properties of the electrode. Metal foil processing with single line and multiple parallel lines is shown in Figure 7a.

![Figure 7a](image)

**Figure 7a.** Slit profile model diagram.

The copper foil with thickness of 40 µm was used for laser multi-parallel cutting with laser cutting speed of 150 mm/s, pulse repetition frequency of 80 KHz and processing times of 10 times. Figure 7b shows the relationship between the slit width and the spacing of two parallel lines during laser processing. When the line spacing gradually increases from 10 to 30 µm, the slit width gradually increases from 30.2 to 50 µm.

![Figure 7b](image)

**Figure 7b.** Relationship between slit width and number of laser parallel lines at the same laser cutting line spacing (20 µm). It can be seen that the slit...
width increases from 20 to 100 μm when the laser parallel lines are increased from 1 to 5 with the same spacing. The cut width of a single laser on copper foil is about 20 μm, and the cut width is theoretically about 30 μm when the distance between two parallel lines is 10 μm. Multi-parallel cutting incision line width is increased by a multiple of single-line incision line width. This method can effectively enlarge the slit width and improve the success rate and efficiency of stripping to a certain extent. The width of the cut can be adjusted according to different needs, and fewer parallel lines can be selected to improve the processing efficiency without affecting the processing and stripping. The ablation zone is controlled by multi-parallel cutting technology. The width of the cut is enlarged while the micron copper electrode is patterned, and the interference to the target electrode is reduced during stripping. Compared with single-line machining, the heat-affected zone is not increased and the influence on the stretchable substrate is reduced.

Figure 7. (a) Schematic diagram of multiple parallel line cutting. (b) Variation of slit width with spacing of parallel lines; (c) variation of slit width with number of parallel lines.

3.4.2. Laser-Assisted Stripping of Excess Copper Foil

Laser can be used to directly scan the local small area of the interface material, resulting in the phenomenon of microstructure change and local deformation of the sample, so as to realize the stripping of the upper film and the substrate, and facilitate the transfer of printing on the recipient substrate or the transfer of micro devices [22,23]. Of large-area excess copper foil is easy to peel, but the local small area of copper foil is harder to distinguish to the naked eye or excess detachment (especially in electrode populated area), for these areas can use the high speed laser scanning way, make its produce deformed, at the same time corresponding to the bottom of the colloid viscosity decreased, pulled away from the basal part area, so that it can be identified by the naked eye and removed smoothly. Figure 8 shows the laser assisted stripping process. In the experiment, the copper foil in the target area was scanned at a high speed (10,000 mm/s, 100 KHz) by laser according to the predetermined pattern. After scanning the excess metal area, part of the area was deformed by heat and warped from the base. After laser treatment, the copper foil was easily stripped manually.

Figure 8. Laser assisted manual stripping process.
4. Results

4.1. Circuit Packaging

After the stripping is completed, weld the electronic components in the corresponding position, check and package. The circuit board was placed in a mold, perfused again with Ecoflex, cured at room temperature for 24 h, and packaged. The single packaged circuit packaged in accordance with the above configuration is shown in Figure 9. A LED is lit after the power supply is switched on.

![Figure 9](image-url)

**Figure 9.** Packaging for stretchable circuits. (a) Schematic diagram of single circuit packaging; (b) single LED package.

4.2. Tensile Properties Test

In order to verify the tensile properties of the stretchable electrode, a horseshoe interconnect electrode with a length of 5 cm and a thickness of 40 µm was prepared by the above double parallel line cutting method and tensile test was conducted, as shown in Figure 10. The results show that the horseshoe interconnect electrode can withstand about 50% tensile deformation without damage, and the wire can be restored to its shape after release. When the tensile change was 0–60%, the resistance increased from 4.019 to 4.071 Ω; when returning to the initial position, the resistance decreased to 4.054 Ω, with a maximum relative change of about 1.3%, this kind of electrode has high resistance stability and superior electrical conductivity compared with gel electrode and graphite electrode. When the tension reaches more than 60%, fracture occurs at the apex of the arc, which is inferred to be the necking of the wire at the stress concentration point.

![Figure 10](image-url)

**Figure 10.** Tensile testing of single electrodes. (a) Tensile test bench; (b) tensile test (strain 10–50%); (c) electrode fracture (strain 60%); (d) resistance strain characteristic curve.
4.3. Typical Applications

A 3 × 3 LED array circuit was fabricated by the above process. As shown in Figure 11, the array circuit is mixed with 9 LEDs. The array circuit is 32 mm long and 18 mm wide. The copper foil with thickness of 40 μm was selected, and the double parallel line laser cutting with line spacing of 10 μm was adopted. The excess copper foil outside the wire was stripped by laser assisted to prepare the electrical layer, and the LED was welded on the pad and packaged. The results of deformation test show that the circuit can work normally under bending, folding and torsion. After 50% tension, the circuit still maintains good electrical and mechanical properties.

![Image of LED array](image1.png)

**Figure 11.** Stretchable LED array. (a) LED array circuit structure; (b) packaged LED array; (c) bending and torsion tests; (d) tensile test.

As shown in Figure 12, a flexible temperature measuring circuit is further made, the maximum thickness of the finished product is 3.5 mm, which is composed of electronic components such as microcontroller, temperature sensor, driver and 28 light-emitting diodes, among which the light-emitting diodes are combined into digital shape for displaying two decimal numbers and real-time dynamic display of temperature values. Design wire interconnection circuit according to electrical schematic diagram, then weld and package the circuit, stick it on the wrist to measure skin surface temperature. With the stretching or bending of the wrist, the flexible temperature measuring circuit attached to the human wrist can realize its function, the temperature of the wrist is measured at 31 °C; the temperature measured on the outer wall of a water cup is 48 °C, which shows that the technology has certain application value.

![Image of temperature measuring circuit](image2.png)

**Figure 12.** Stretchable temperature measuring circuit. (a) Schematic diagram of temperature measuring circuit; (b) electrode diagram of temperature measuring circuit; (c) application test of temperature measuring circuit.
Figure 11. Stretchable LED array. (a) LED array circuit structure; (b) packaged LED array; (c) bending and torsion tests; (d) tensile test.

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Figure 12. Stretchable temperature measuring circuit. (a) Schematic diagram of temperature measuring circuit; (b) electrode diagram of temperature measuring circuit; (c) application test of temperature measuring circuit.

5. Conclusions

In this paper, a process for fabricating stretchable electrodes based on ultraviolet laser direct writing technology is proposed. The influence of the main laser processing parameters on the cutting quality is analyzed through experiments, and the patterning of copper foil is realized. In this study, low-cost raw materials and processing equipment were used to prepare interconnected electrodes with a stretchable structure through laser direct writing technology. After embedding the interconnected electrodes into elastomers, a wide range of cyclic stretching can be achieved to meet the work needs of the daily environment. The process realizes high-efficiency and low-polluting manufacturing, and provides a feasible idea for the large-scale manufacturing of stretchable circuits. On this basis, multi-layer circuits can be constructed to meet the control requirements of more complex functions.

Author Contributions: C.L. conceived and designed the work; L.D. and Y.F. conducted the experiments; M.Z. and X.Q. analyzed the data; L.D. and Y.F. wrote the manuscript; K.F. and Z.Z. reviewed and revised the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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